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FEASIBILITY, OPERABILITY AND ECONOMIC STUDIES FOR ENERGY SOURCES FROM RENEWABLE AGRICULTURAL WASTE AND OTHER BIOMASS

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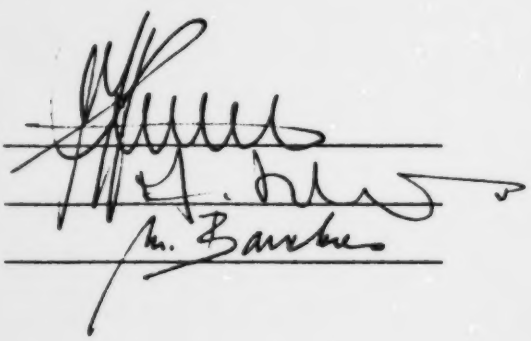

EXECUTIVE SUMMARY

In 1977, the Saskatchewan Power Corporation initiated a feasibility study on production of electricity from wood in small isolated northern communities in Saskatchewan. The principal conclusions of that program indicated that wood gasification followed by combustion of low-energy produced gas in a modified diesel engine can be an attractive alternative to electricity generation from diesel fuel. The Corporation decided to conduct field trials using a commercially available wood gasifier from Imbert Energietechnik in West Germany. A model F6L413FR (65 kVA) gasifier-motor-generator was acquired in 1979 and assembled on a mobile platform first for testing in Regina, then for field trials in Jan Lake, Saskatchewan.

During tests in Regina, the system performed satisfactorily. Several mechanical problems developed such as failure of the grate mechanism, air infiltration around the air divider, and bridging of the bed, but they were corrected either by changing the design of the system or by modifying the operational procedures.

The produced gas heating value was in the range of 4.5 to 5.5 $MJ \cdot m^{-3}$ with gas composition dependent on the gasifier temperature, and gas heating value being constant over a wide range of load variation. The gasification efficiency was between 75 and 80 percent. The efficiency for conversion of wood to usable electricity was dependent upon the load and varied from 4 to 14 percent for 20 to 80 percent of the generating capacity (65 kVA). Wood consumption varied slightly for different species at higher loads, but was the same for all species at no load conditions.

The engine-generator maintained a steady voltage and frequency and responded rapidly to electrical load changes, stabilizing the frequency within several seconds. Loss of frequency was observed when bridging of wood chips occurred in the gasifier bed or during the refueling of the gasifier due to air infiltration into the system.

Analysis of electricity cost over a ten year period using wood gasification-motor-generator vs diesel generator has indicated a levelized electricity cost in constant 1981 dollars equal to 0.204 $/kWh for wood and 0.130 $/kWh for diesel system. High labor charges for wood gasification made it less attractive; however, an analysis of key economic parameters showed that a significant reduction of electricity cost can be obtained for wood systems if additional automation were introduced at a moderate increase of capital cost. The successful completion of a seven day run on 1982 May 12, in Regina, and potential for reduction of electricity cost were instrumental in recommending the continuation of the project with Phase II, field testing in a Co-op site at Jan Lake, Saskatchewan.

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1. INTRODUCTION

1.1 Background

Through its subsidiary, North Sask Electric, the Saskatchewan Power Corporation operates a number of diesel powered electric generating units to provide electricity for essential services in remote and isolated northern communities. It is for these communities that the SPC's studies on long-range energy demand and pricing have indicated that wood gasification followed by combustion of wood gas in an internal combustion engine can be an attractive alternative for electricity generation (SPC R & D Report, 1977). All northern communities have plentiful wood resources and a wood gasification plant can be easily scaled to the size of the community.

Following a critical examination of available commercial gasifiers, the Saskatchewan Power Corporation decided to conduct testing and field trials of a gasifier-engine-generator set. The Corporation has chosen a downdraft gasification system equipped with a gas engine. The Corporation acquired a wood gasification power plant Model F6L413FR (Figure 1.1) from Imbert Energietechnik in West Germany. A brief description of the power plant and preliminary test runs are given in the SPC Interim Report (1980).

1.2 Project Objectives

The primary objectives of the program conducted under the EMR/DSS contract OSQ78-00146 have been defined:

- To survey small and medium size gasification units and to acquire a

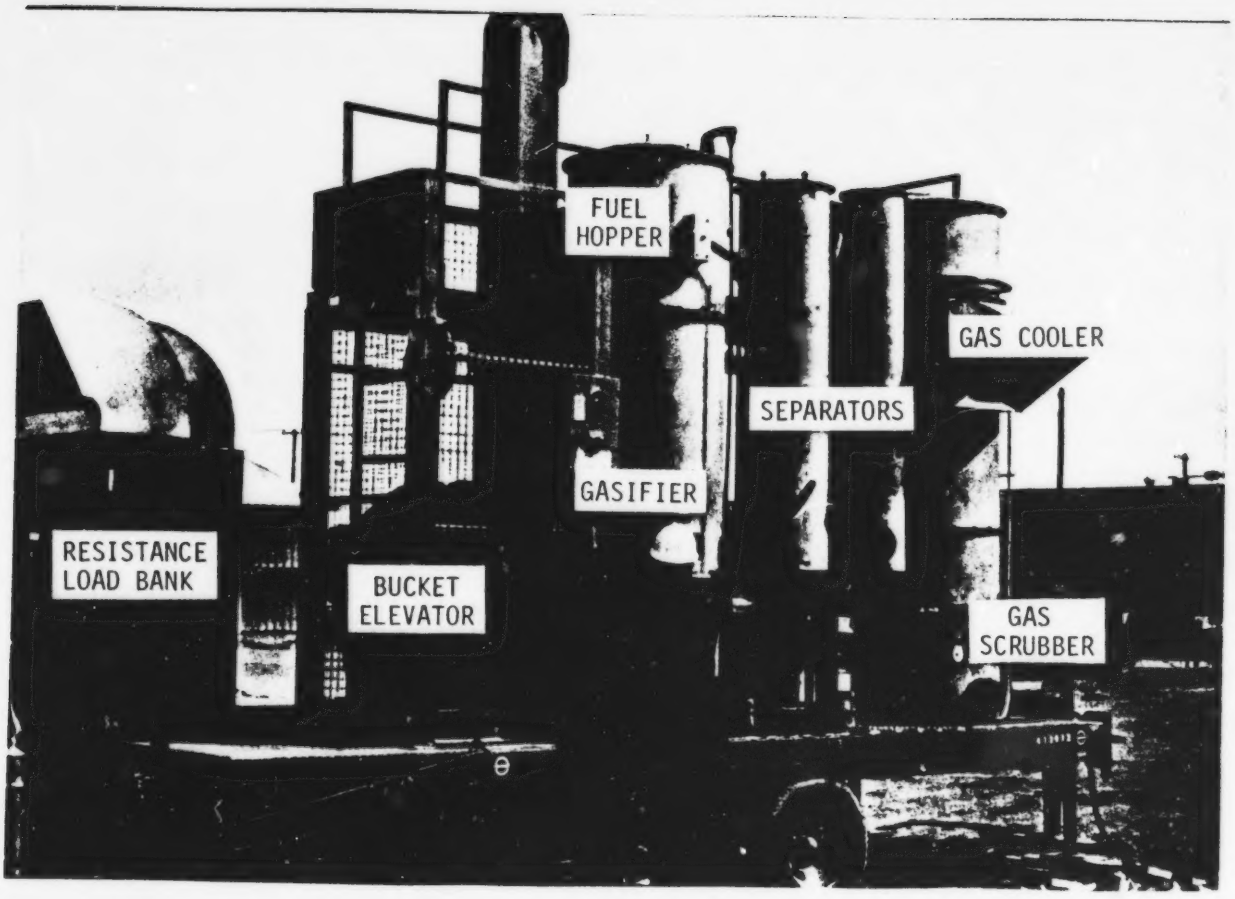

Figure 1.1. IMBERT Wood Gasification Power Plant Model F6L431FR

prototype for operations in Saskatchewan.

- To assemble the unit for tests in Saskatchewan.
- To assess the operability, reliability and engineering of the acquired prototype.
- To evaluate the economics of electricity generation using a wood gasification-motor-generator system.

1.3 Program Scope and Organization of Report

The project scope included modification of the loading hopper and ash removal system by the manufacturer at the request of SPC. In addition, several minor design modifications were introduced throughout the program to improve the system performance. Major engineering changes such as automation of the feeding system, redesign of the reactor vessel to prevent bridging, and redesign of the ash removal grate were considered beyond the scope of the program.

The performance of the gasifier system was analyzed in terms of gas composition and calorific value as they are related to the electrical load and the performance of the modified diesel engine. To determine the thermal efficiency of the unit, all gas streams were characterized including various energy flows, gas stream composition, etc. These data are reported in Section 4. Section 3 describes each run including comments on the operation, load, and test performance. The test numbers are coded, and indicate the electrical load, type of wood, and run number.

Section 5 contains an economic analysis and summary of various fixed and operating costs. The performed sensitivity analysis indicates several possible routes for further system improvement with the cost of electricity remaining fixed.

Conclusions and recommendations are presented in Section 6 including the need for further development programs and for engineering design changes in wood gasification motor-generator sets.

2. SYSTEM DESCRIPTION

2.1 Design

2.1.1 Gasifier

The gasifier consists of two concentric cylinders forming a double walled vessel. The bottom section of the inner cylinder forms the hearth or gasification zone. Five tuyeres originate from a common air chamber in front of the gasifier; one of the tuyeres is in direct line with the air intake of the chamber and allows a view inside the hearth when the unit is in operation. Figure 2.1 shows the inner vessel and hearth section.

The air chamber is bolted to the outer shell and a high temperature gasket prevents air from entering the space between both shells. During operation air enters through the front opening and is drawn into the hearth via the tuyeres. A flapper valve, located at the back of the air intake, closes off the air supply when gas is no longer demanded and stops the gasification process by halting the air supply to the hearth. This valve also prevents an escape of toxic and flammable gases from the hearth via the tuyeres after shutdown.

There are three circular inspection ports to check the charcoal level in the outer shell at the tuyere level (Figure 2.2). An additional port for cleaning and inspection is located at the front of the outer shell below the air intake. This port also provides access to the grate.

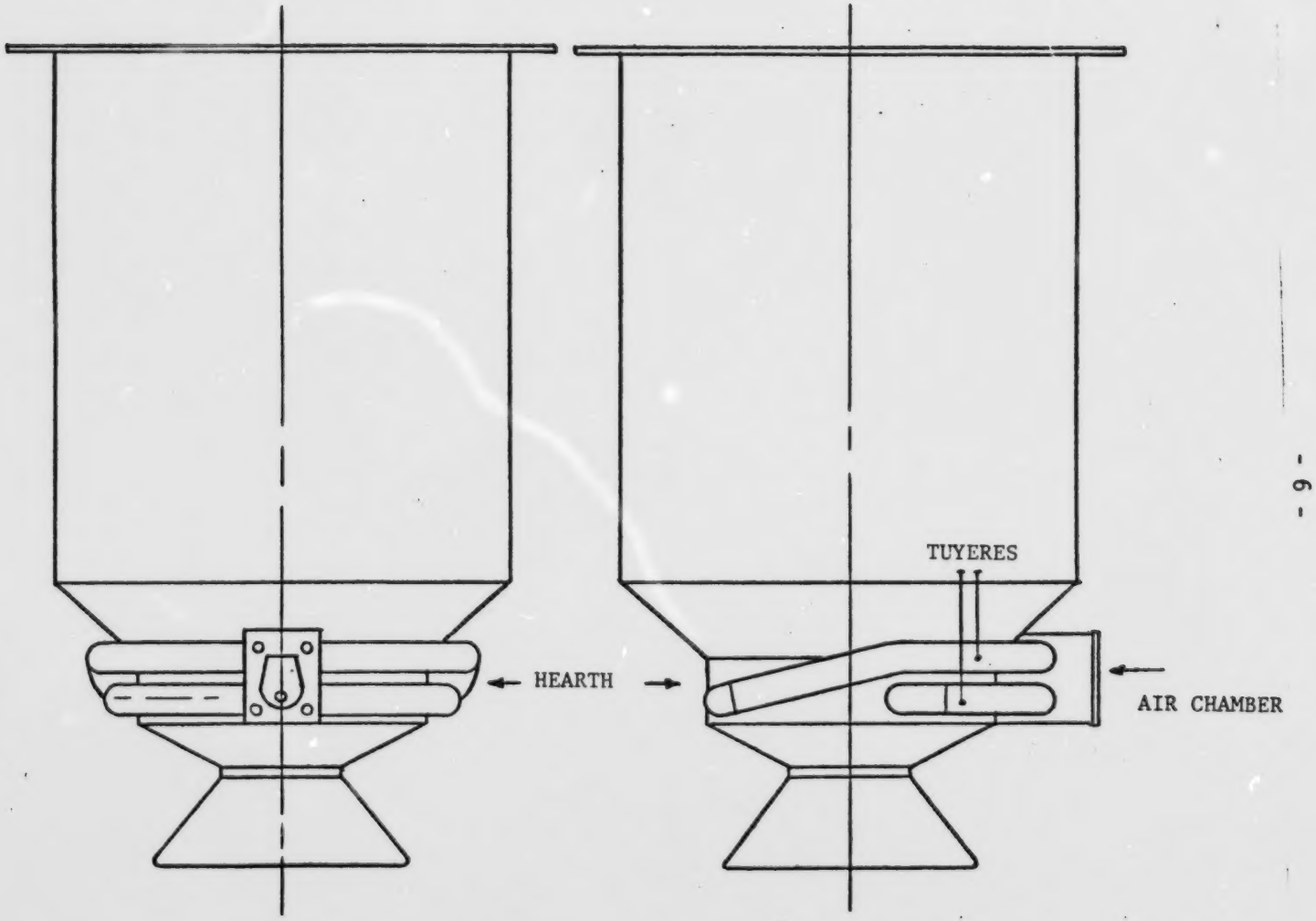

Figure 2.1. Inner Vessel with Tuyeres and Hearth Cone

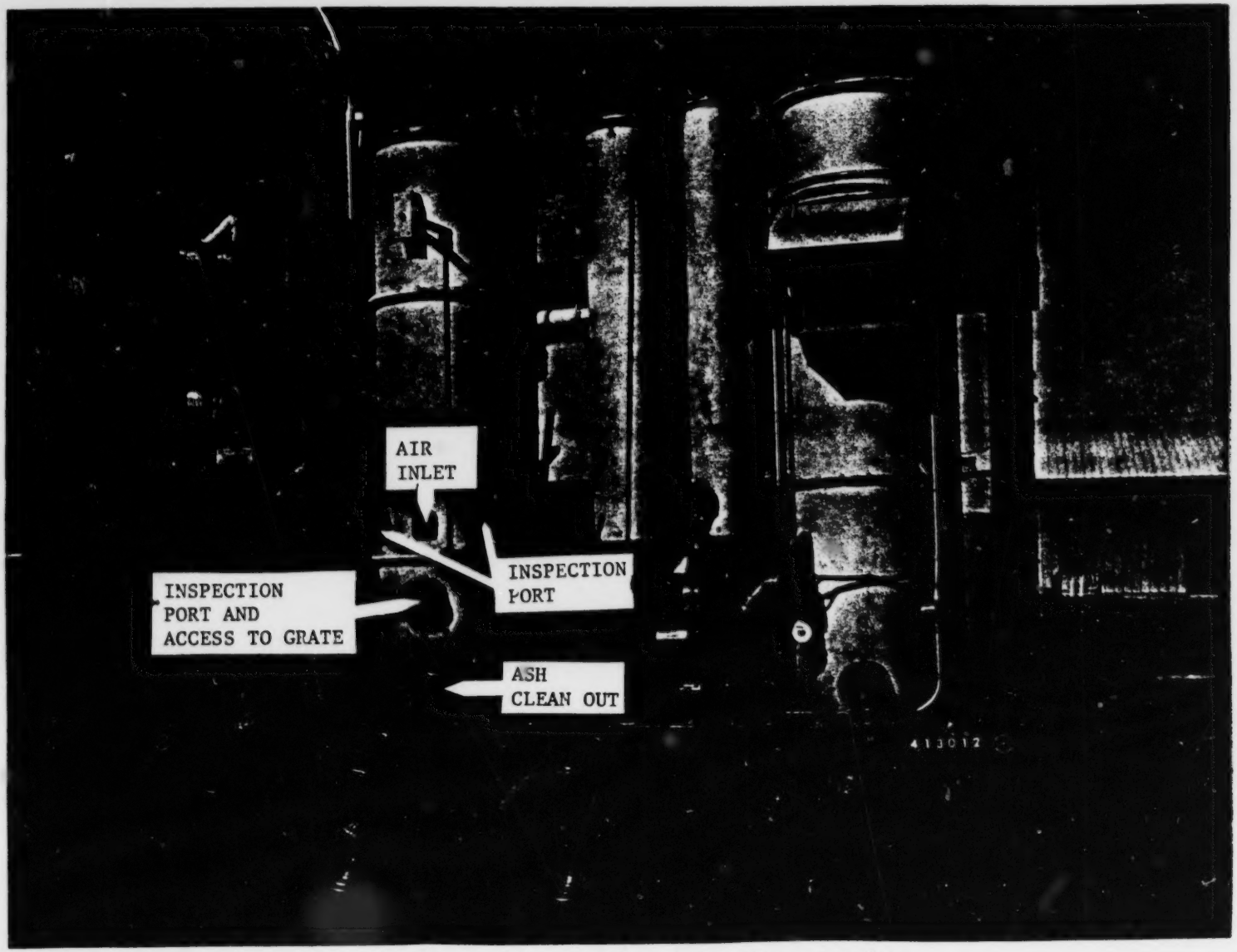

Figure 2.2. Gasifier Motor-Generator Set

Below the grate are the grate drive and ash box. The ash box can be cleaned via a rectangular lid from the bottom. The grate drive consists of three toggles which lift the grate approximately 2 - 3 cm and then suddenly drop it to remove the ash from the charcoal. (Figure 2.3).

A fuel hopper is located at the top of the gasifier. The hopper allows refueling of the gasifier without electrical power interruptions. A set of doors located inside the hopper prevents air from being drawn through the top during refueling. These doors can be operated manually via a lever at the front of the gasifier. A second lever operates the top lid of the hopper. There is no interlock on the lever mechanisms allowing both doors and lid to be operated independently, or simultaneously.

2.1.2 Gas Cleaning and Cooling

The gas cleaning system consists of three dust separators, a washer, a gas cooler and a demister. In the washer (Figure 2.4), the gas is contacted with water before entering the gas cooler. An access port at the bottom of the washer permits periodic sludge removal. Water is continuously recycled from the sludge tank and sprayed in the cooler. The spray washes down any condensate formed on the cooler walls and also promotes condensation of water from the saturated gas. The water level in the sump is controlled by a float which operates a motorized valve. If the water level in the sump rises excessively as a result of condensation, sufficient water is discharged to return the level to between the set limits. A low water level would not sufficiently clean the gas,

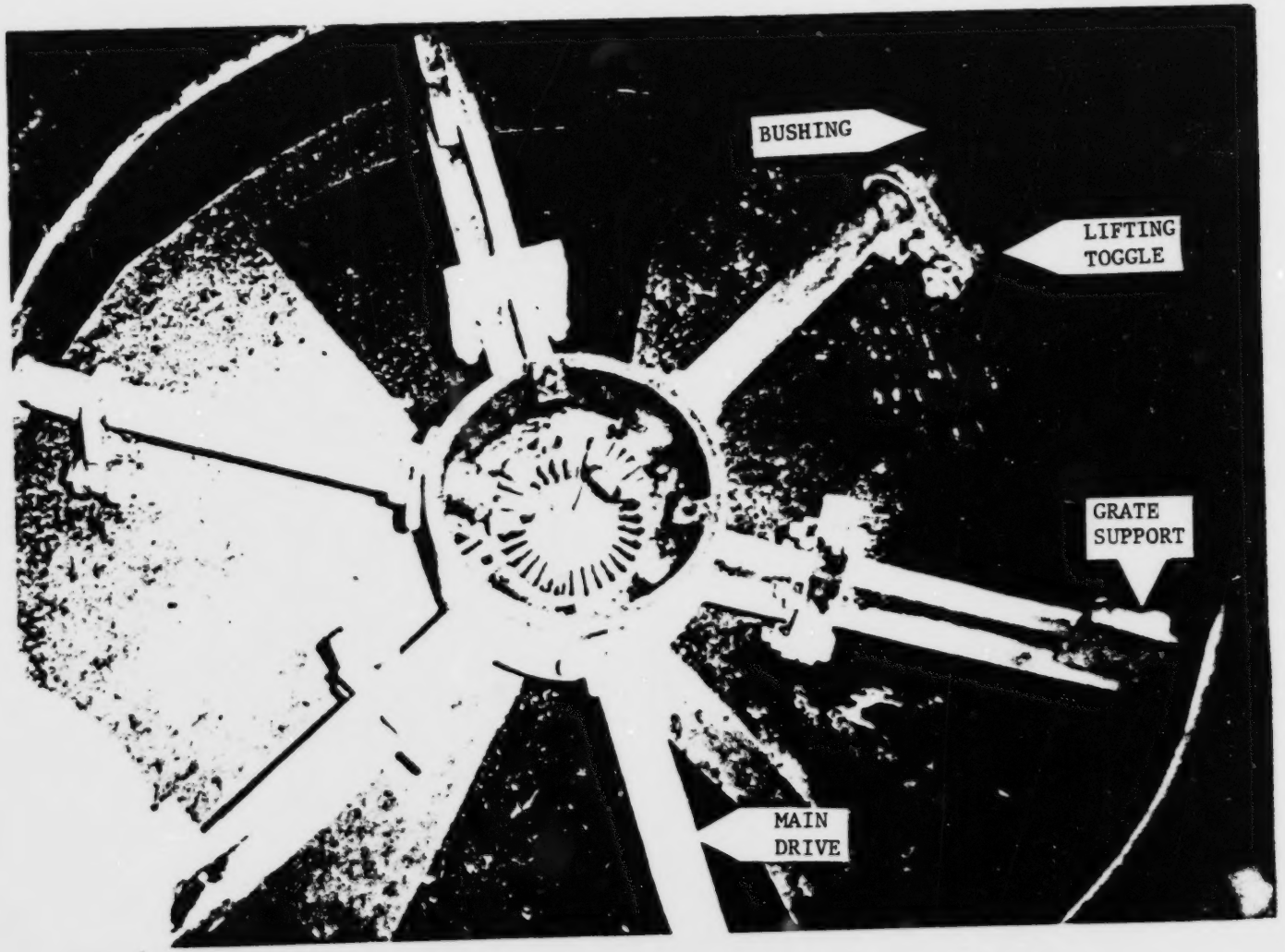

Figure 2.3. Grate Drive Mechanism. Grate and Cover Plate of Bevel Gear Box have been removed.

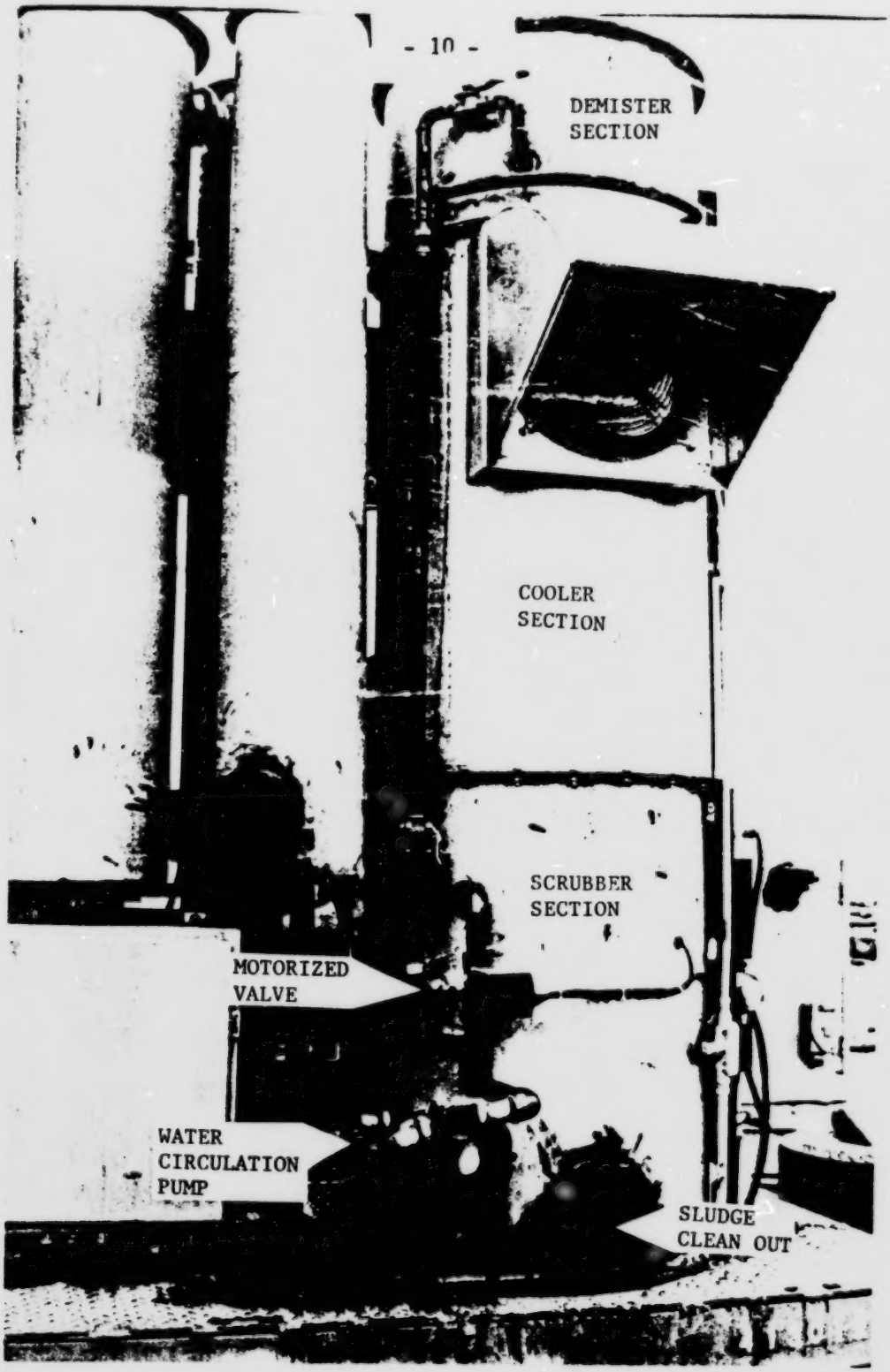

Figure 2.4. Gas Scrubber and Cooler

while too high a level would increase the pressure loss and reduce the volumetric efficiency of the engine.

The demister is located on top of the gas cooler. The demister bottom is perforated and contains a 20 cm layer of 5 mm sized cork. The cork can be removed or loaded through a spring loaded lid on the top of the demister. The cork is prevented from being drawn into the gas supply line by a second screen.

2.1.3 Engine

The gasification system was purchased with a Deutz air-cooled Series 413 diesel engine modified for operation on low-Btu gas only. The six cylinder engine (Model F6L413FR), shown in Figure 2.5, has an axial type cooling air blower driven by twin V-belts. An automatic V-belt tensioning device has a breakage monitoring system to stop the engine in case of belt breakage and to prevent subsequent cooling failure. The engine's fuel pump and injectors were removed and replaced by a distributor and spark plugs respectively (Figure 2.6). The engine is rated for 85 kW at 1500 r/min or 92 kW at 1800 r/min for diesel fuel operation. The cylinder bore is 125 mm with a stroke of 130 mm, yielding a piston displacement of 9572 cm^3.

Conversion from diesel to low Btu gas operation decreases the rating of the engine. The decrease results mainly from the lower heating value of the generator gas. The heating value of the wood gas/air/moisture mixture is usually 2.5 - 2.6 MJ/m^3. This means that it is

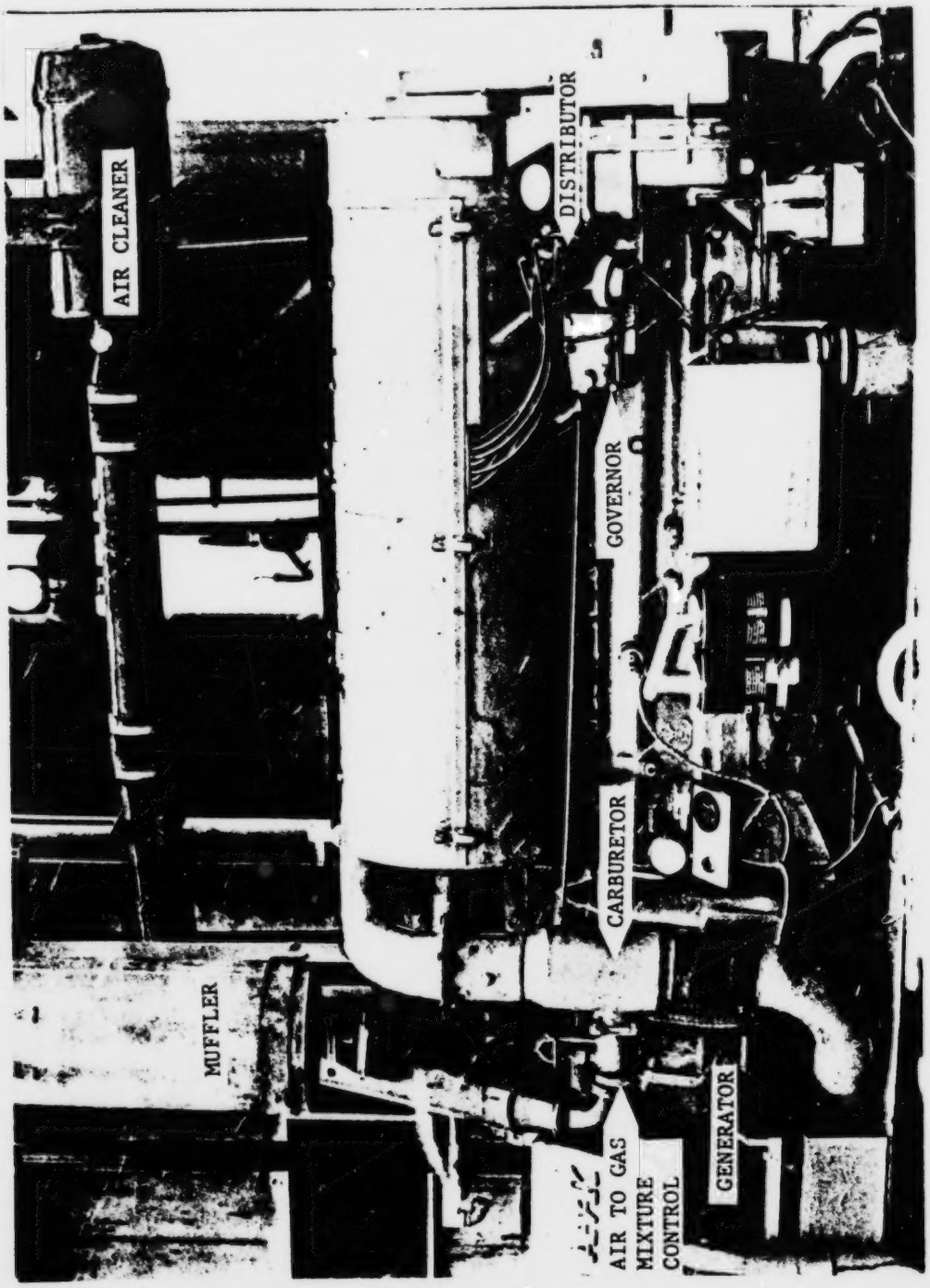

Figure 2.5. Modified Deutz Diesel F6L413FR

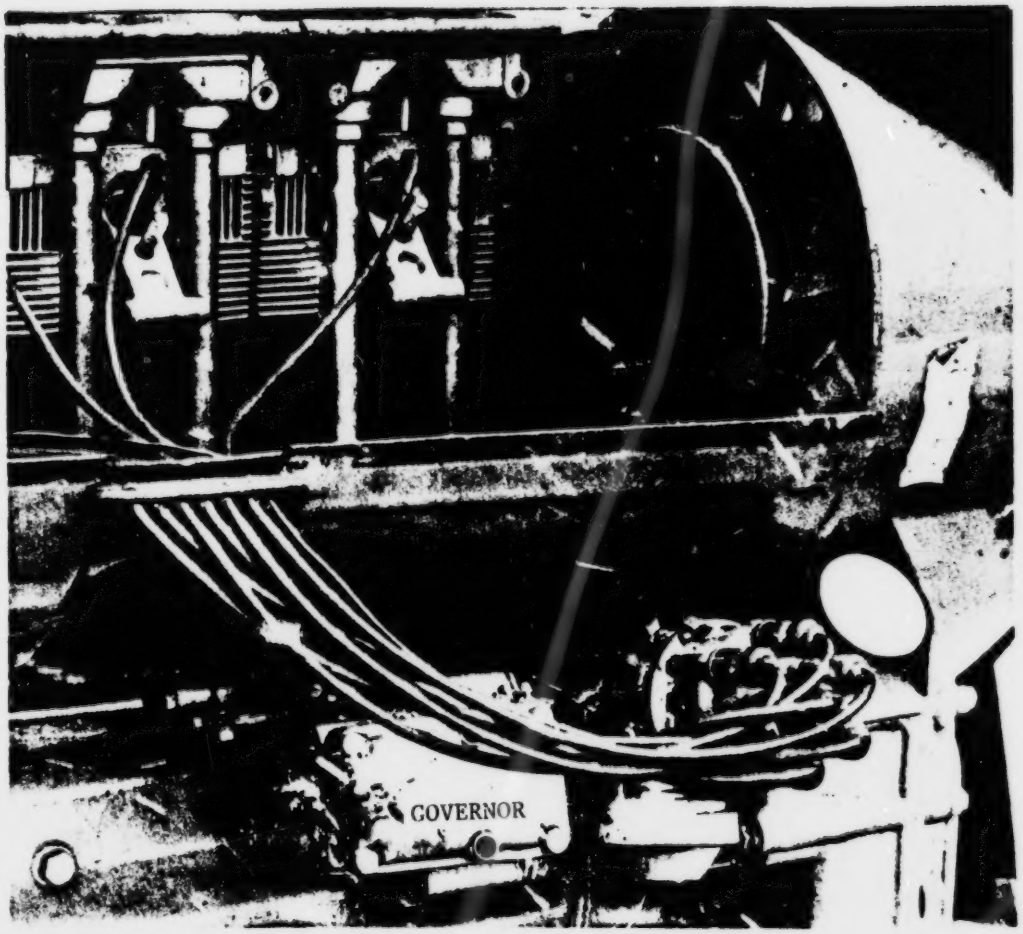

Figure 2.6. Engine Detail

possible to obtain only 70 percent of the diesel rating by conversion to low Btu gas. Pressure losses in the gasifier and associated gas purification system further reduce the gas/air mass to the engine and cause a reduction in volumetric efficiency.

2.1.4 Generator

The generator is an Arthur van Kaick generator rated at 65 kVA ($\cos \phi = 0.8$). The generator is directly coupled to the engine and rotates at 1800 rpm.

2.2 Operating Principle

The Imbert wood gasifier is a downdraft suction gasifier. Engine suction draws gasification air into the reaction zone where it is chemically combined with a partially charred wood to form carbon oxides. The involved principle is thus opposite to the principle in air blown gasifiers where air is forced into the reaction zone and the resulting increase in pressure expels the produced gas.

In a downdraft gasifier the amount of produced gas always matches the gas demand and no extensive gas regulating equipment is required. Downdraft suction gasifiers are, therefore, ideal for applications where frequent changes in gas consumption are required, e.g. motor vehicles and electric generators. Another advantage of suction gasifiers is prevention of toxic or combustion gases escaping into the surroundings through minor leaks. A major disadvantage of the system is the reduction of the volumetric efficiency of

the engine caused by operation at reduced pressures.

In a downdraft gasifier wood is transformed into a charred wood before it enters the combustion zone. The gasification zone is located below the combustion zone with the reduction taking place in the charcoal bed above the ash grate. The charcoal bed is replenished during operations with charred wood. Under a steady load the rates of formation and consumption of charred wood are equal and maintain a constant char level above the grate. With variations in load and moisture in wood the charcoal bed may be depleted, affecting the gas composition, principally the water content.

In downdraft gasifiers moisture from wood passes through the combustion zone, thus maintaining the bed temperature and providing the heat required for the endothermic reaction of water with char. This places an effective limit on the maximum moisture content of wood (about 30 percent).

The changes in gas composition and heating value are automatically counteracted by adjustments of the butterfly valve via the engine governor. When the engine stops, gas is no longer withdrawn from the gasifier and gasification of wood is also interrupted. However, the charcoal bed remains glowing for another 3 to 5 hours during which the unit can be restarted without the need for relighting the charcoal.

The exit gas is routed through the dust collector and scrubber to reduce the content of particulates and water. An additional sludge collecting tank is placed downstream of the scrubber to collect the condensed moisture and fine dust which have precipitated in the pipe connecting the scrubber and engine.

A diesel engine can be modified either for operation on a low-Btu gas exclusively or for operation on dual fuel (diesel fuel and low-Btu gas). Modifications for operation on low-Btu gas require a relatively extensive rebuilding of the engine. The engine must be fitted with cylinder heads accommodating spark ignition, new pistons, and a complete electric ignition system. In a dual fuel engine, modification of only the injection system is required. A summary of relative disadvantages and advantages of both systems is presented in Table 2.1.

Table 2.1. Comparison of Conversion to Gas Only or Dual Fuel Operation

	Advantages	Disadvantages
Dual Fuel	Simple to Convert Better Startup	Reduced Power
Gas Only	More Economical Operation	Extensive Rebuilding

3. TEST PROGRAM

3.1 Experiments and Measurements

The studies were conducted using three wood species: 1) Jack Pine (Pinus Banksiana) mixed with two percent of tamarack (Larix Laricina); 2) White Spruce (Picea Glauca); 3) Trembling Aspen (Populus Tremuloides). Jack pine and white spruce were obtained from the area south of Montreal Lake, Saskatchewan, which was destroyed by a fire in 1978. The trembling aspen was obtained from a road clearing near Hudson Bay, Saskatchewan. The moisture content of jack pine varied from 7.8 to 15.0 percent. For white spruce and trembling aspen the moisture content varied from 9.4 to 24.3 percent and from 13.7 to 28.0 percent respectively.

A total of 24 thermocouples (Figure 3.1) were monitored at 5 minute intervals during all experimental runs. The thermocouples were spring loaded to maintain contact with the inner jacket and to compensate for the difference in expansion between the outer and inner vessels. All thermocouples were K-type (chromel-alumel).

The air flow rates to the gasifier and engine carburetor were measured using hot wire anemometers TSI models 2016 and 2017. These models correct for temperature and pressure changes and measure volumetric flow rates (L/min) at standard reference conditions (Appendix A). Flow rates of the product gas stream were determined from measurements of differential and static pressures and temperatures at the orifice meter placed in the gas supply line to the engine (Figure 3.1). An AGA computational method was used to determine

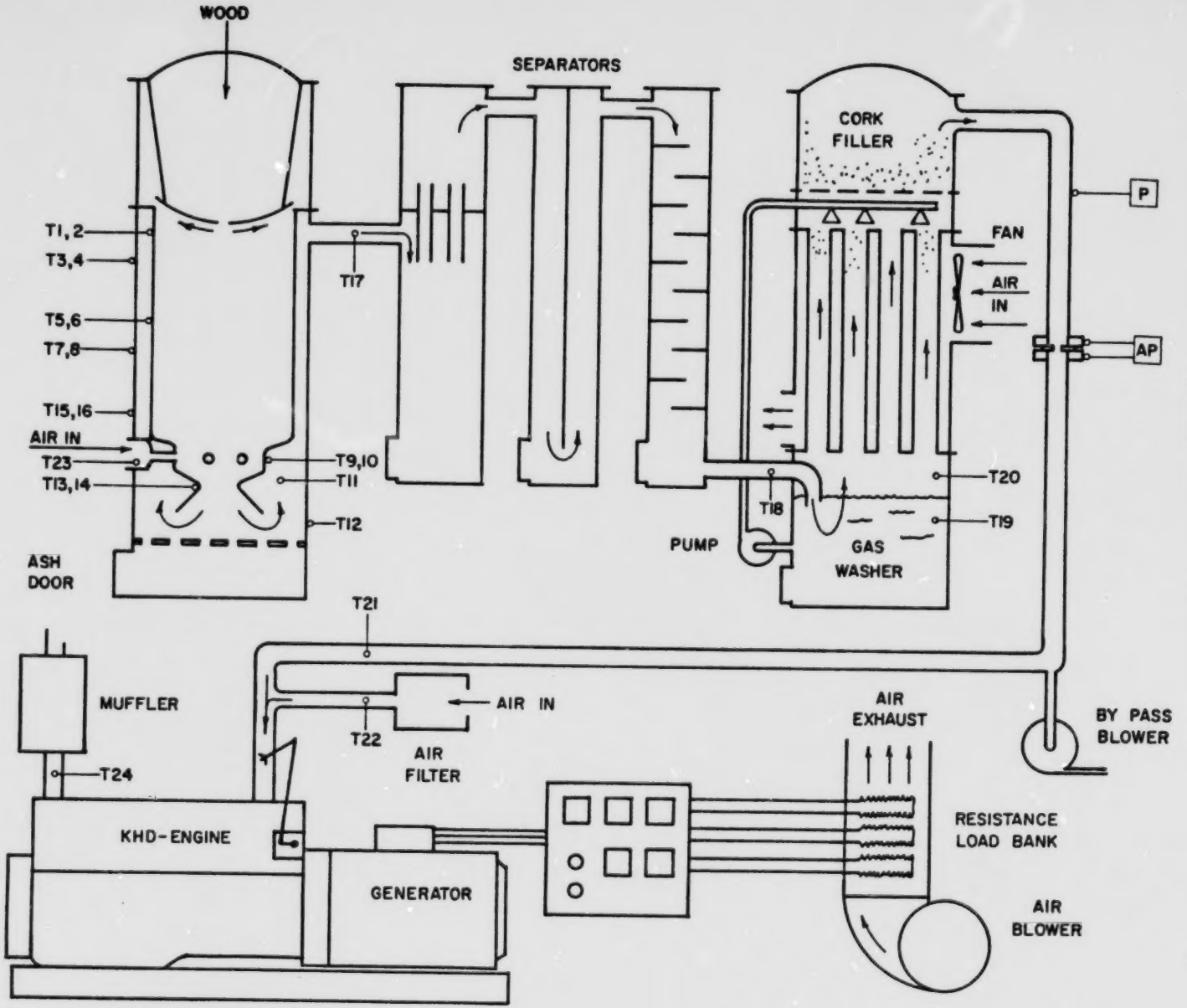

Figure 3.1. Schematic Drawing of Imbert Wood Gasification Plant

volumetric and mass gas flow rates from the pressure, temperature and gas composition measurements (Appendix A).

Since the gasifier operates below atmospheric pressure, gas samples were withdrawn from the gas supply line to the engine using a Gast Rotary Vane oil-less gas pump. Gas sample bags and infrared monitors for CO, CO_2 and CH_4 were mounted downstream of the pump. The gas sample bags were periodically filled and analyzed for CO_2, CO, CH_4, H_2, O_2/Ar and N_2 using a Fisher Model 1200 gas partitioner. These concentrations were used to compute gas heating value, density and other properties.

All measured temperatures, pressures, and signals from the IR Analyzers and flow transducers, were periodically scanned and recorded using a Digitec 3000 data logger.

Wood was prepared in a Kopohogger PH-10 Chipper manufactured in Finland by KOPO-Konepohja (Figure 3.2). The chipper was equipped with a 15 kW(e) electric motor; however, it could be also driven from the tractor. The chipper, when equipped with the electric motor, could handle logs up to 10 cm diameter for jack pine, tamarack and white spruce, and up to 15 cm diameter for trembling aspen producing chips with an average size of 5 x 5 x 0.5 cm (Figure 3.3).

Wood loads were weighed to the nearest 0.1 kg and moisture content of each load was determined using a moisture analyzer. A typical moisture distribution curve is shown in Figure 3.4. Table 3.1 presents the average moisture content and the total amount of wood consumed for each experimental run. The runs are coded as follows: 1) the first two digit number indicates

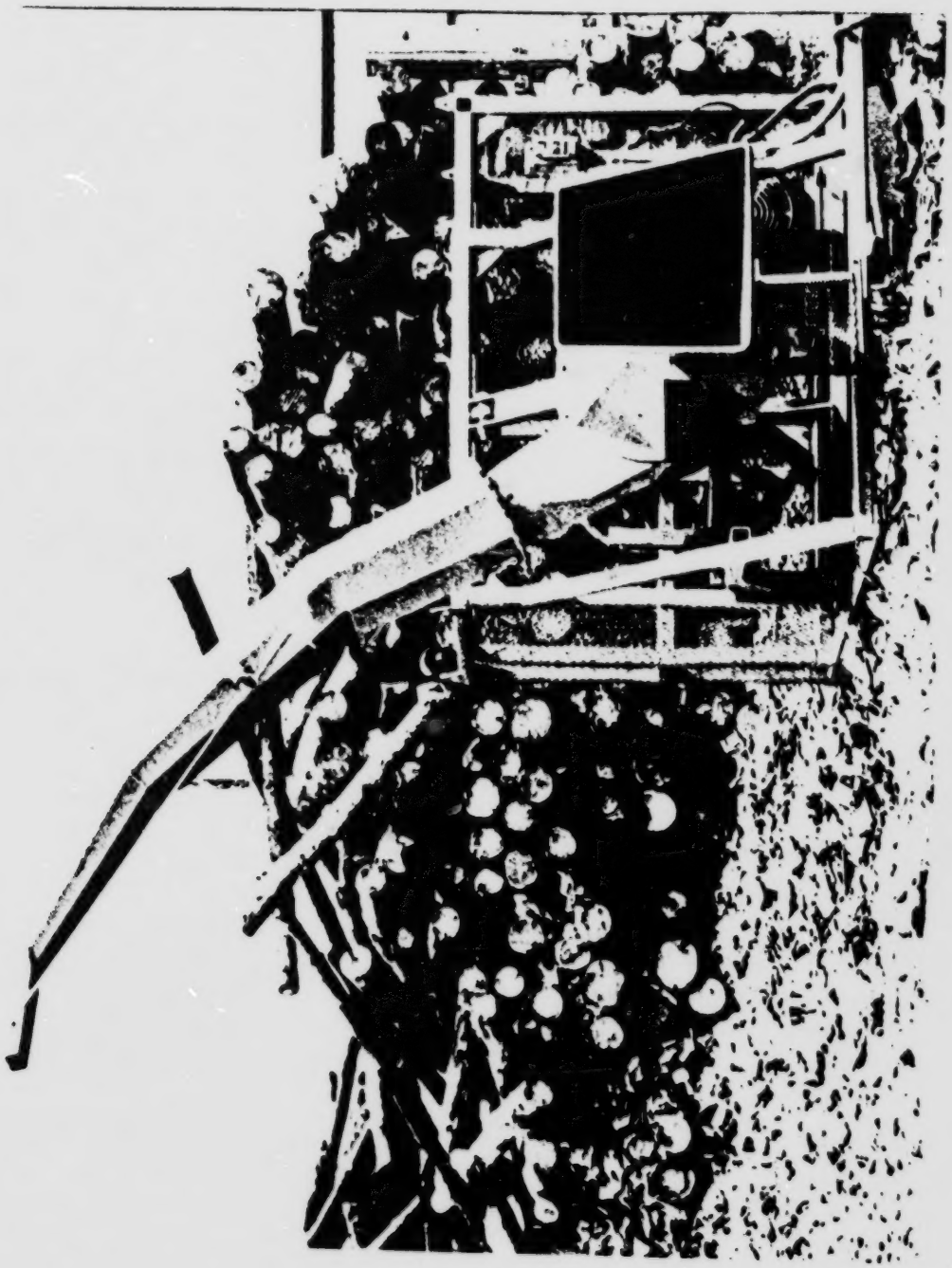

Figure 3.2. KOPO PH-10 Wood Chipper

Figure 3.3. Wood Chips as Obtained from the KOPO PH-10 Wood Chipper and Used in the Tests

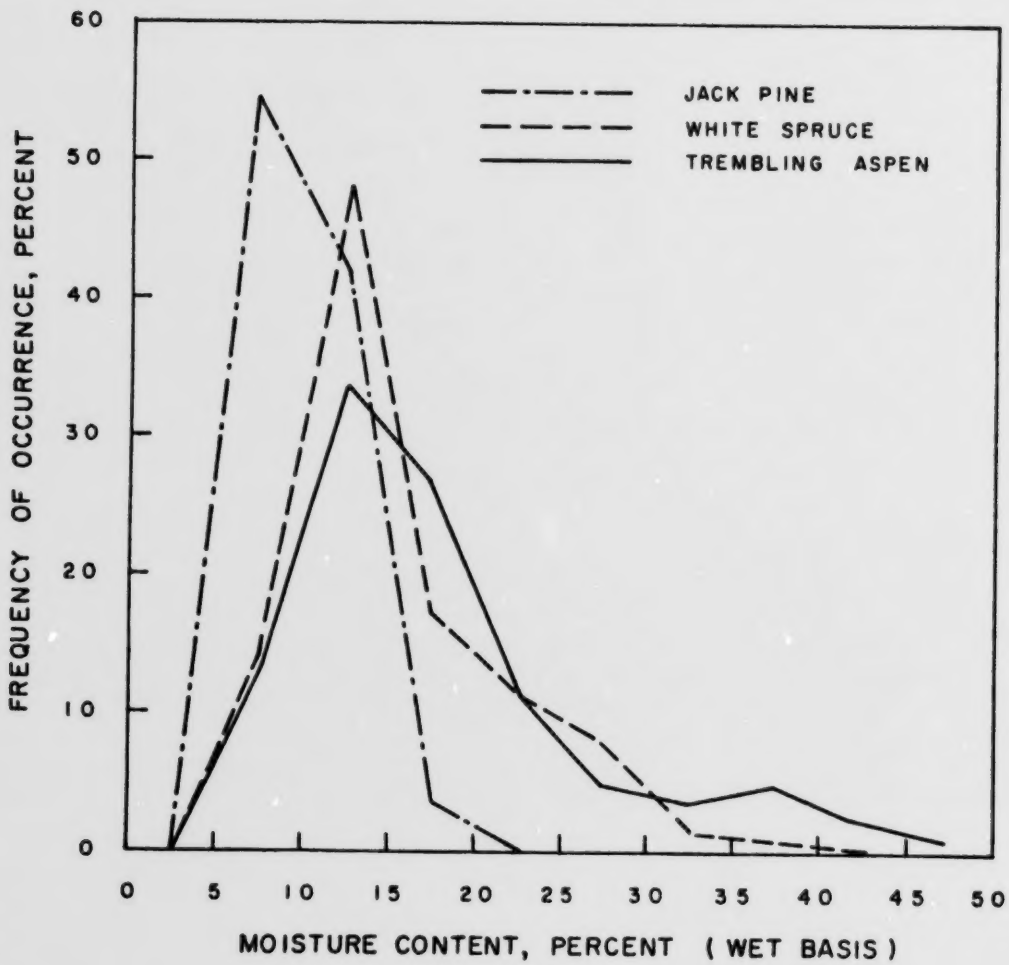

Figure 3.4. Frequency Polygon for Moisture Content of Wood Fuels Used in the Test Runs

Table 3.1. Test Run Parameters

Run	Electric Load % Rated Cap.[a]	Durations[b] min.	Wood Consumed kg (moisture)[c]	Electricity Generated[d] kWh
45JP-01	86.5	420	316.0 (9.8%)	240.3
30JP-02	57.7	394	254.8 (9.9%)	187.4
15JP-03	28.8	411	252.9 (13.0%)	102.2
45JP-04	86.5	331	295.8 (12.3%)	224.2
30JP-05	57.7	342	258.7 (12.1%)	156.2
15JP-06	28.8	395	231.2 (11.2%)	100.5
05JP-07	9.6	131	-- --	3.5
VJP-08	Variable	260	174.4 (10.0%)	90.0
15JP-09	28.8	332	180.2 (8.8%)	80.4
05JP-10	9.6	431	186.1 (9.5%)	37.1
30JP-11	57.7	130	-- --	48.7
30JP-12	57.7	166	-- --	79.2
15JP-13	28.8	16	-- --	3.4
15JP-14	28.8	--	-- --	0.0
VJP-15	Variable	338	248.4 (12.0%)	215.9
20JP-16	38.5	107	51.0 (12.2%)	31.4
30WS-16	57.7	230	171.1 (11.7%)	113.7
20WS-17	38.5	402	242.4 (12.3%)	70.3
10WS-18	19.2	384	187.1 (11.7%)	70.3
40WS-19	76.9	362	353.3 (19.6%)	228.2
40TA-20	76.9	398	320.2 (17.1%)	218.1
35TA-21	67.3	410	350.4 (20.7%)	240.2
20TA-22	38.5	382	248.8 (16.2%)	131.4
10TA-23	19.2	333	163.9 (20.2%)	61.3

[a] max. rated capacity 65 kVA ($\cos \phi = 0.8$)

[b] included startup time and recovery times

[c] moisture on wet basis

[d] net output to consumer

the electrical load in kW; 2) the following alphabetical characters stand for wood species (JP-jack pine, WS-white spruce, TA-trembling aspen); 3) the last two digits indicate the run number.

In each run, the gasifier was loaded with fresh charcoal briquettes to a level just below the tuyeres and with wood chips up to the lower hopper doors. The load was lit by inserting a combustible material (e.g. paper) into the front air intake and lighting it with matches while operating the suction fan on the battery. After several minutes of operation on the suction fan, the engine would be started. The engine would be idled about 1 minute before the electric load was applied.

The gasifier was refueled immediately after startup using the bucket elevator. The average wood charge was about 25 kg. Each subsequent charge was introduced into the hopper when the lower (inner) hopper doors could be closed. This procedure ensured the same level of chips in the gasifier when starting and completing the run. The wood consumption for the run would be then equal to the sum of the weights of the added loads. The procedure resulted in an error of less than two percent for the total wood consumption on dry basis.

Table 3.2 shows the frequency of engine stoppages (power outages) due to bridging of the charge in the gasifier. In most cases, the engine was quickly restarted after poking the load through a special capped nipple welded in the top of the hopper. To avoid extensive bridging a strict refueling procedure was followed in all runs:

1. Each charge was poked to ensure that wood was not bridging.

Table 3.2. Unschedule Outages During Test Runs

Run #	Duration[a] min	Unscheduled Outages	Frequency Below 55 Hz[b]	Poked n Times	Fuel Added n Times
45JP-01	420	2	5	--	14
30JP-02	394	1[c]	3	18	10
15JP-03	411	1[c]	7	8	11
45JP-04	331	2	7	9	12
30JP-05	422	3[c]	5	12	10
15JP-06	395	--	2	14	9
05JP-07	131	3[c,d]	4	1	--
VJP-08	260	2	6	13	7
15JP-09	332	2[c]	2	14	7
05JP-10	432	1[c,e]	1	14	8
30JP-11	130	2	2	2	4
30JP-12	166	1[d]	4	--	3
15JP-13	16	--	--	2	2
15JP-14[f]	--	--	--	--	--
VJP-15	338	4	9	6	10
20JP-16	107	1	1	3	2
30WS-16	230	1	3	10	7
20WS-17	402	4	5	15	10
10WS-18	384	2[c]	3	11	8
40WS-19	362	4	17[g]	3	14
40TA-20	398	1	7	1	13
35TA-21	410	--	1	--	14
20TA-22	382	--	1	5	10
10TA-23	333	--	1	3	6

[a] Includes startup and recovery time.

[b] If frequency did not recover within 30 seconds, the load was reduced and this was also counted as an unscheduled outage.

[c] One engine stalling within 10 minutes from startup.

[d] Forced shutdown.

[e] Difficult to start.

[f] Cannot start engine due to poor gas quality.

[g] Reduction in frequency during refueling.

2. The inner set of doors were closed.
3. A full elevator basket was raised above the hopper.
4. The top hopper door was opened and the charge was thrown into the hopper.
5. The empty bucket was returned and the hopper door closed.
6. The inner hopper doors were opened.
7. The refueling cycle was repeated when the inner doors could be closed.

Additional descriptions of detailed startup and operation for Runs 45JP-01 through 10TA-23 are given in Appendix B.

The generator was electrically loaded using three 25 kW(e) electric resistance furnaces. The generator connection was a floating Y and the furnace loads were adjustable in discrete steps of 5 kW(e) each. Each furnace was equipped with a kWh meter allowing readings to be taken before and after the run. When the engine stalled, the electric load was established immediately after the engine was restarted.

3.2 Breakdowns and Corrective Actions

The number of breakdowns was larger than anticipated. Table 3.3 gives the type of breakdowns, the action taken, the total hours of operation and the time required to correct the problem.

Minor problems such as a defective elapse timer, etc., did not prevent the system from operating and could be corrected during the scheduled shutdowns for ash removal. Breakdowns of the water circulation pump in the scrubber required shutdown only when the system was operated at high loads for

Table 3.3. Major Equipment Malfunctions

Problem (Corrective Action)	Approx. Hours of Operation h	Electricity Generated kWh	Time Needed For Repairs h
Front bearing in startup fan seized. (Replaced front and rear bearings.)	0	0	8
Elapse timer not working. (Replaced timer.)	5	128	(1)[a]
Motor for water circulation pump on the gas scrubber burned out. (Replaced pump and motor.)	13	334	8
Throttle tarred up, engine does not follow load changes. (Removed and cleaned carburetor.)	14	340	4[b]
Fan Motor on the gas cooler burned out. (Replaced motor and fan.)	19	372	4[c]
Broken wire in electronic ignition system. (Fixed wire.)	29	436	4[d]
Support screen for cork filter plugged. (Cleaned screen.)	40	537	2
Inner doors in lock hopper seized.	44	580	(16)[e]
Elapse timer not working. (Replaced timer.)	45	609	(1)[a]
Drive chain for the fueling bucket broke. (Fixed chain.)	61	1058	(3)[f]

Table 3.3. Major Equipment Malfunctions (Cont'd.)

Problem (Corrective Action)	Approx. Hours of Operation h	Electricity Generated kWh	Time Needed For Repairs h
Water circulation pump on the scrubber failed, due to broken impeller. (Replaced pump and motor with heavy duty type.)	65	1138	6
The outer mantle of the reactor glowed, as a result of air leakage around the air divider box. (Replaced gasket.)	85	1623	6[g]
Grate mechanism defective. (Replaced pin in main bevel gear.)	95	1794	16[g]
Startup fan made excessive noise. (Replaced front bearing.)	107	1959	(6)[a]
Grate mechanism defective. (Replaced pin in main bevel gear.)	123	1962	8[g]
Broken wire in electronic ignition system. (Fixed wire.)	123	1962	.5
Grate mechanism defective. (Replaced pin in main bevel gear.)	150	2945	6[g]
Grate chain drive defective. (Repaired drive and checked pin in main bevel gear.)	154	3017	16
Grate mechanism defective. (Main bevel gear damaged.)	163	3456	10 days

Table 3.3. Major Equipment Malfunctions (Cont'd.)

Problem (Corrective Action)	Approx. Hours of Operation h	Electricity Generated kWh	Time Needed For Repairs h
Bottom section of hearth cone separated, due to weld failure. (Disassembled reactor and rewelded cone.)	163	3456	3 days

[a] Times in brackets indicate that no operational time was lost due to this problem.

[b] The air intake was modified to prevent condensation of residual organic vapours in the carburetor. Time for these modifications is not included since it constitutes improvement and not repair.

[c] The unit was operated for approximately 3 hours without the fan, during which time a replacement was obtained. The hours refer to wiring changes due to incompatibility between North American and European voltage levels.

[d] 3-1/2 hours was spent to diagnose the problem.

[e] This problem is the direct result of an operational error, and therefore not counted as lost time. However, design changes could prevent this.

[f] The unit was kept in operation by manual refueling, via buckets.

[g] This does not include minimum set hours of cool down time required.

an extended period of time. Failure of the water circulation system led to carburetor fouling and associated engine problems. The lack of cooling also caused higher gas temperatures and reduction in the engine output.

Failures of the grate drive mechanism and air infiltration around the air divider box were the most serious operating problems. They resulted directly from the design errors in the gasifier. The leakage around the air intake was corrected by a periodic tightening of the bolts. The original cap nuts were replaced with regular nuts and spring washers to ensure a good seal. A further improvement of the design could be obtained by the use of an expansion sleeve which would reduce material stress and would correct for differences in expansion between the inner and outer vessel.

Problems with the grate drive mechanism were caused by difficulties with the shaft bearings. The shaft ends were positioned in glide bearings inside the ash box without any possibility for lubrication (Figure 2.3). Both, the main bevel drive and the gear pin failed during testing because of seizing of the two idler shaft bearings. The grate was operated despite the failure of the pin, but it eventually warped due to being lifted at one position only. The design of the grate drive was improved by installing grease nipples for lubrication. This could be further improved by locating the shaft ends and bushings outside the vessel for easy periodic inspection.

The most serious problem with the gasifier occurred during preparation runs for field testing. The bottom section of the hearth cone separated as a result of a weld failure at the throat (see Figure 3.5). Also, the bevel gear was damaged and the shaft broken at the pin (Figure 3.6). Both problems were corrected before the field trials which are described in the field test report.

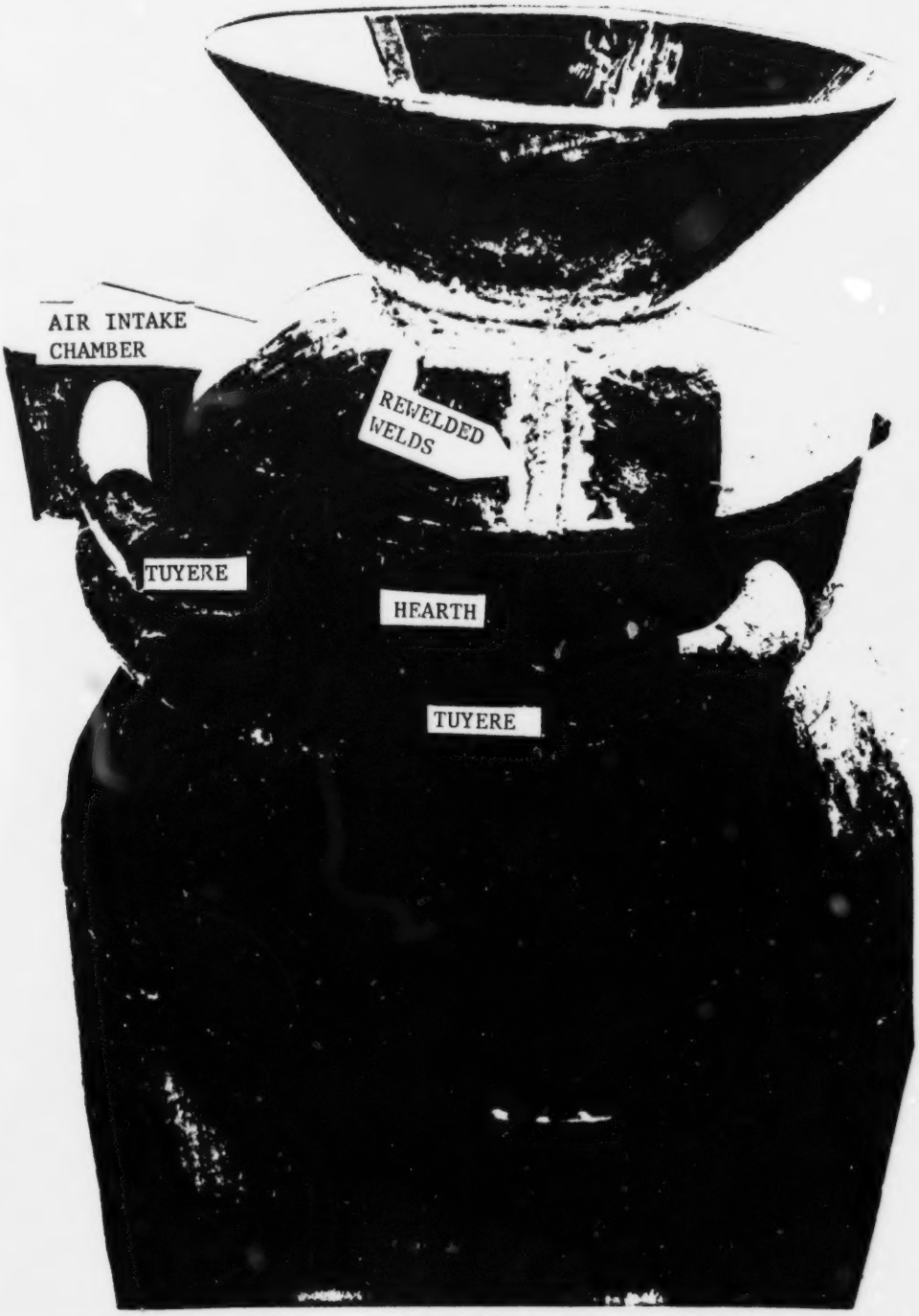

Figure 3.5. Inner Vessel with Hearth Cone, Showing Rewelded Sections

Figure 3.6. Main Bevel Gear with Fractured Main Drive

4. RESULTS AND DISCUSSION

4.1 General System Performance

Startup of the unit was fast, requiring less than 3 minutes after lighting the gasifier. However, with fresh chips and insufficient charcoal in the hearth the startup would often be delayed for as much as 45 minutes while the hearth attained gasification temperatures. In using charcoal in the gasification zone for startup, the drying and charring cycles are omitted and a very high hearth temperature is established almost immediately.

At constant loads, the unit performed well, maintaining a steady frequency of 60 Hz $\pm$ 1/2 Hz. At loads less than 15 kW(e), the line frequency was above 61 Hz, but this could be corrected by adjustment of the governor linkage. Since the engine speed is controlled by the governor, the air to gas ratio in the carburetor intake had little effect on the frequency. The air to gas setting was more critical for operation at high electrical loads and it was adjusted to a position where the throttle was in the most closed position.

The changes in electrical load were handled reasonably well. For example, removing the entire electrical load at 45 kW(e) caused the engine to overspeed for approximately 2 seconds after which the rotational speed stabilized at a line frequency of about 62 Hz. Reapplication of the load after one minute resulted in a stabilization of frequency at 60 Hz within 2 to 3 seconds. This rapid system response was facilitated primarily by the large

gas volume in the cleaning system and by the constant engine speed (1800 $r.min^{-1}$) even at zero electrical load. The large gas volume between the gasifier and engine can act as a buffer for a sudden increase or decrease of gas demand by the engine. Since a constant speed is maintained at zero load, the result is a high temperature in the gasifier hearth throughout operations thus permitting fast changes of the gasification rates.

A significant concern about the acceptable performance of the unit in the forthcoming field trials was raised by many sudden stoppages during the testing. These problems were caused by wood bridging in the hopper and hearth. Frequent poking and inspection of the bed partially eliminated the stoppages; however, a complete solution of the problem would require a redesign of the inner reactor vessel with a slight tapering and reduction of the diameter towards the top. As delivered, the vessel was a straight cylindrical shell without the required tapering for free downward movement of the bed charge.

We have not observed tar in the gas and waste water stream during the operation. The scrubber water did not show even a trace of oily deposits or substances. The filtered and dried sludge from the scrubber resembled a black powder collected in the ash/char separators. Deposits in the pipes downstream of the gas cleaning train were moist, black and easy to remove after drying. These deposits were formed because the scrubber system is under-sized.

4.2 Gas Quality and Composition

Appendix C shows the gas composition for the majority of tests. In all cases, the gas composition tends to be determined by thermodynamics and is independent of the system load, i.e. gas production rate (Tables 4.1 and 4.2). There is a strong correlation between the hearth temperature and mole fractions of CO, CO_2, and CH_4. Figure 4.1 shows the interrelation between the CO and CH_4 typical for a system controlled by a thermodynamic equilibrium. The effect of gas composition on the heating value is shown in Table 4.3.

4.3 Overall System Efficiency

The overall system efficiency was determined by conducting a series of tests in which the gasifier-engine-generator set was run for an extended time at constant electrical load. The total amount of electricity generated and the total amount of wood consumed were used to calculate the system efficiency.

$$\text{Efficiency } \% = \frac{\text{Usable Electrical Energy}}{\text{Energy in Wood}}$$

The total amount of wood gasified was at least three times the volume of the reactor (about 180 kg dry basis). The estimated error in measurements of wood consumption was on the order of 4 to 10 kg (moist basis) or 2 to 6 percent of the total charge. This error would include all measurement errors, i.e. determining the level of wood in the reactor, moisture in the wood, and weighing. It does not include the amount of charcoal consumed outside the hearth, which for most runs was too small to be considered significant.

Table 4.1. Average On-Line Gas Analysis

Run	CO_2 Vol. %	CO Vol. %	CH_4 Vol. %	H_2O* Vol. %
45JP-01	10.4	16.4	2.1	6.4
30JP-02	11.4	19.1	1.5	6.0
15JP-03	11.1	19.3	1.5	5.8
45JP-04	13.0	18.2	1.7	7.9
30JP-05	12.3	18.8	0.9	7.2
15JP VJP-08	10.3	18.1	1.8	6.5
15JP-09	8.8	18.2	1.5	6.1
05JP-10	9.9	19.3	2.0	4.8
VJP-15	11.1	16.9	1.5	7.6
20JP-16	9.1	19.3	0.7	3.1
30WS-16	11.3	17.6	1.7	7.7
20WS-17	10.4	19.0	1.5	7.0
10WS-18	10.5	18.3	1.5	10.0
40TA-20	12.1	17.7	1.8	8.3
35TA-21	12.9	16.7	1.9	8.4
20TA-22	13.4	17.5	2.1	6.7
10TA-23	12.2	16.7	2.2	5.7

* Calculated assuming saturation.

Table 4.2. Average Gas Composition in Mole Fraction and Heating Value as Determined by Gas Chromatograph

Run	No. of Gas Samples	CO_2	CO	CH_4	H_2	N_2	O_2/Ar	Heating Value[a] $MJ.m^{-3}$
30JP-02	17	9.9	18.4	1.2	18	49.2	2.8	4.9
15JP-03	11	9.7	18.1	1.0	20	49.0	2.8	4.9
45JP-04	9	11.1	15.5	1.3	20	49.0	2.9	4.7
30JP-05	4	11.6	15.0	1.4	20	49.8	2.5	4.6
15JP-06	13	12.0	13.6	2.0	18	50.5	3.7	4.6
VJP-08	15	8.8	17.0	1.3	15	53.6	4.0	4.3
15JP-09	13	8.4	16.0	1.0	15	54.4	4.9	4.1
20JP-16	7	8.4	18.4	0.8	16	52.0	2.8	4.9
30WS-16	10	11.1	18.0	1.5	20	48.3	3.0	4.9
20WS-17	18	9.8	18.3	1.1	18	50.5	2.8	4.7
10WS-18	23	10.6	18.1	1.2	20	48.4	2.1	4.9
40TA-20	30	11.7	17.9	1.6	23	44.1	1.6	5.5

[a] At 15°C and 101.325 kPa (ISO 5024)

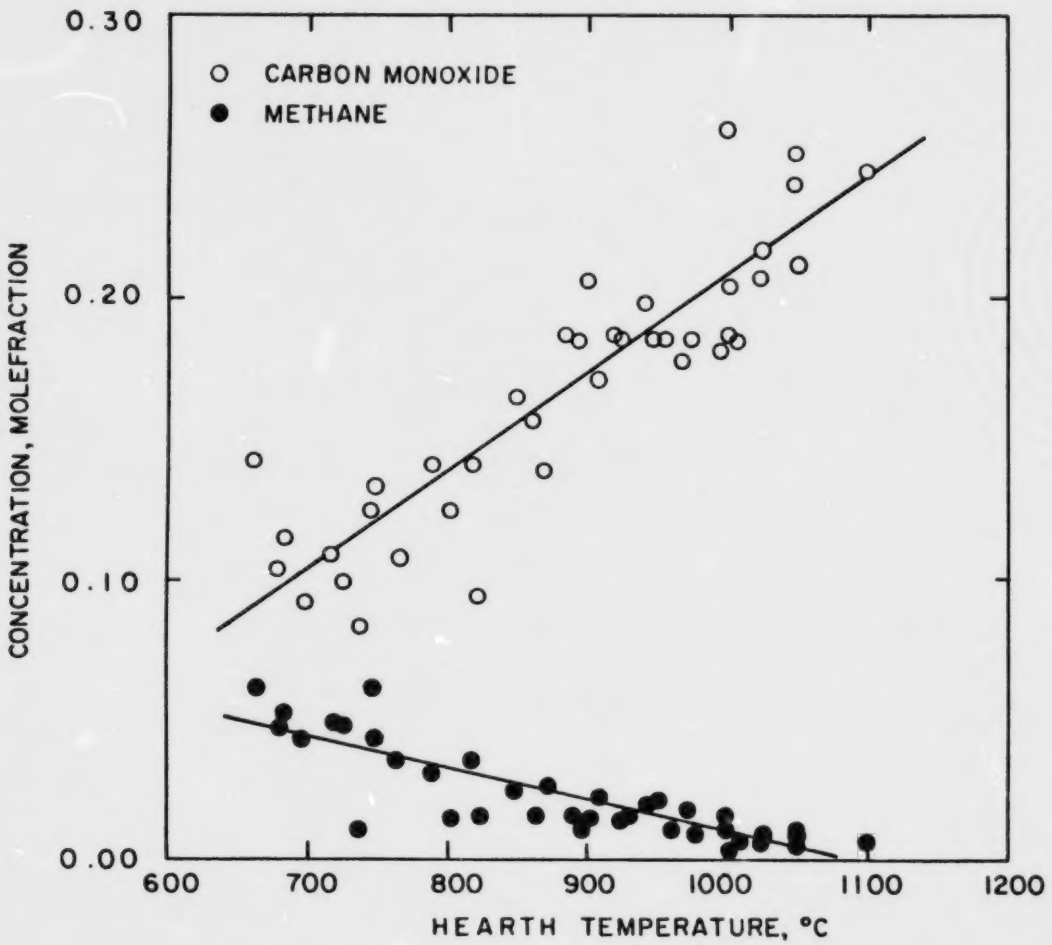

Figure 4.1. Carbon Monoxide and Methane Concentration in the Gas as a Function of the Hearth Temperature

Table 4.3 Changes in Heating Value as a Result of Changes in Gas Composition

Gas Composition, Mole Fraction					Heating Value[a]
CO	CO_2	CH_4	H_2	N_2	MJ/m^3
15.4	10.6	1.4	21	51.3	4.902
16.1	11.1	1.3	20	50.6	4.901
16.7	11.5	1.2	21	49.9	4.899
17.3	12.0	1.1	20	49.2	4.898
17.9	12.4	0.9	20	48.5	4.896
18.5	12.8	0.9	20	47.9	4.895
19.1	13.2	0.7	20	47.3	4.894
19.7	13.6	0.6	19	46.7	4.892
20.2	14.0	0.5	19	46.1	4.891
15.6	11.9	1.1	22	49.0	4.924
16.5	12.0	1.1	21	49.1	4.911
18.2	12.0	1.1	19	49.3	4.884
19.1	12.0	1.1	18	49.4	4.858
20.9	12.1	1.1	16	49.5	4.844
24.4	6.5	1.0	20	48.1	5.677
22.9	7.7	1.0	20	48.3	5.507
21.3	8.9	1.0	20	48.6	5.335
19.7	10.1	1.0	20	48.8	4.161

[a] At 15°C and 101.325 kPa (ISO 5024)

Figure 4.2 shows the energy consumption in MJ per kWh at various electrical loads expressed as a percentage of the rated generator capacity (65 kVA). The system efficiency decreases sharply at less than 35 - 40 percent of the capacity. The hourly wood consumption in kg per hour plotted versus the electrical load shows that up to 20 kg is consumed at no load conditions. This is about one third of the amount consumed under the full load condition (Figure 4.3).

4.4 Mass Balances

Only the carbon balance could be determined with reasonable accuracy. Small leaks and air entrainment during refueling and poking resulted in difficulties in determining the nitrogen balance. Hydrogen balances were also inaccurate without on-line hydrogen monitoring.

The amount of carbon in the product gas was calculated from the average volumetric composition as determined by the Infrared Analyzers at 10 minute intervals. Corrections for moisture were made using gas delivery temperatures and a psychrometric chart. Loss of carbon in the form of deposits formed on the vessel walls and carbon collected in the ash pit and in the three settling chambers was negligible in comparison to the total carbon input.

Table 4.4 shows carbon balances for control runs with all three types of wood. Only run 45JP-01 and 20WS-17 show large deviations. In run 45JP-01 the engine was stalled for an extended period with the startup fan operating in an attempt to restart the engine. In the case of run 20WS-17, low static gas pressures and startup problems may have been responsible for the poor carbon balance. For most runs, however, carbon balances are good or very good.

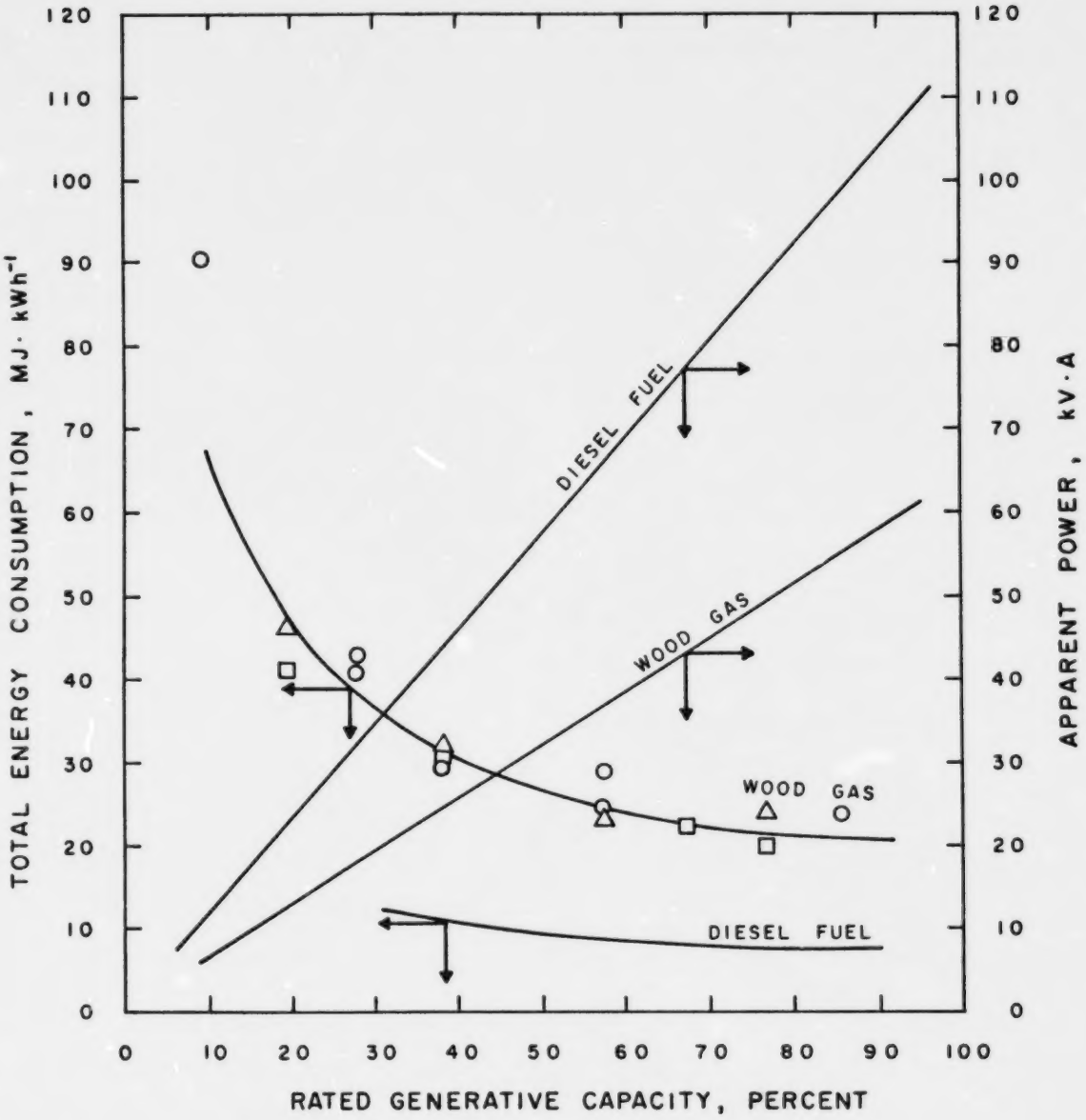

Figure 4.2. Energy Consumption in KHD Engines Model F6L413FR Using Wood Gas or Diesel Fuel Oil

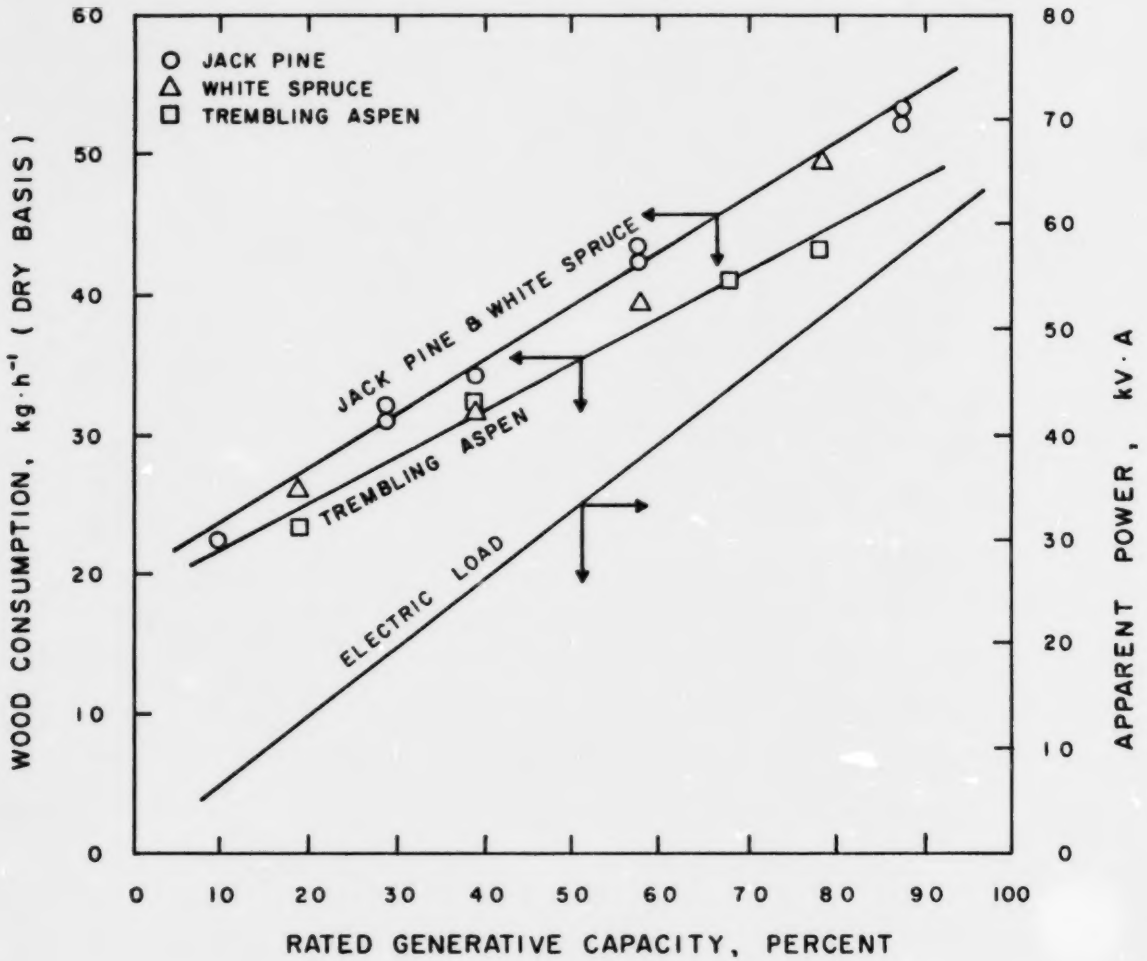

Figure 4.3. Wood Consumption as a Function of the Electrical Load

Table 4.4. Carbon Balances

RUN	45JP-01	45JP-04	30JP-05	15JP-09	05JP-10	20JP-16 30WS-16	20WS-17
Wood (dry), kg	285.1	229.7	227.5	164.3	168.4	195.8	212.6
Air, m^3	--	--	--	--	--	--	--
Gas, m^3	785.4	809.4	705.4	619.7	559.9	621.9	578.3
C in Wood, kg[a]	143.7	130.7	114.7	82.8	84.9	98.6	106.9
C in Gas, kg	107.8	124.5	106.4	84.2	84.4	89.1	84.3
C in Char/Ash, kg	--	4.3	--	--	--	0.6	0.6
Balance OUT/IN	0.75	0.99	0.93	1.02	0.99	0.91	0.79

RUN	10WS-18	40WS-19	40TA-20	35TA-21	20TA-22	10TA-23
Wood (dry), kg	165.2	284.2	265.5	272.9	208.5	130.8
Air, m^3	--	--	--	--	--	303.0
Gas, m^3	565.6	893.9	998.2	933.7	726.8	479.4
C in Wood, kg[a]	83.1	42.9	147.6	144.0	107.2	67.2
C in Gas, kg	82.6	130.7	138.7	136.7	113.6	68.1
C in Char/Ash, kg	0.6	--	3.4	2.8	0.4	2.4
Balance OUT/IN	1.00	0.91	0.96	0.97	1.06	1.05

[a] Carbon in Wood Dry Basis: Jack Pine, 50.4%; White Spruce, 50.3%; Trembling Aspen 51.8%

5. ECONOMICS

5.1 General

In assessing the potential of wood gasification five major questions should be considered: 1) is there a preferable steady year round need for gas to maximize the use of the gasification system; 2) is wood available at an acceptable price; 3) is the price of conventional fuels escalating rapidly and are the supplies reliable; 4) what are the cost and method of financing the gasification facility; and 5) is the gasifier-motor-generator practical to operate under the local climatic, personnel and social conditions? These questions and technical and economic factors such as the system efficiency, the cost of wood and its characteristics, and the system load, will determine the attractiveness of wood gasification for electricity production in a selected community.

Most of the above points can be dealt with in an economic analysis; however, various estimates of future costs, interest rates, etc., are difficult to forecast on the basis of the recent changes in energy pricing. One should note, however, that the escalation and discount rates have little effect on the levelized cost of electricity as long as the real discount rate (the difference between the interest and escalation rates) is kept fixed at some percentage.

The supply of wood is the most important element in wood gasification. In the case of downdraft gasification, waste wood such as produced by a sawmill operation is only partly useable. The feedstock as specified by

Imbert has definite size constraints and only pieces close to an average size of 100 mm x 50 mm x 80 mm can be utilized. The feedstock can, however, contain up to 10 percent sawdust or shavings without causing a large pressure drop across the hearth.

5.2 Evaluation of Equivalent Fuel Costs

In order to offset the retrofit and investment cost, any alternative technology or fuel must provide a sufficient incentive and reduction of operation cost. A simple measure of the attractiveness of a new fuel or technology is the payback period on an investment or a combination of the net reduction of operating and capital costs. Since diesel generators and wood gasifiers require fuels of different energy content to be converted to electricity at different overall efficiencies, we have calculated a fuel "equivalent" cost for wood which incorporates the difference in the energy cost, but does not contain the cost of fixed capital and interest on the investment.

Figure 5.1 shows the "equivalent" fuel values for diesel fuel and wood with different moisture content. One should note that for wood with a high moisture content, an additional loss of efficiency will occur due to the sensible heat of water in product gases. Thus, wood with lower moisture has a premium value. The lines in Figure 5.1 represent a break even point for fuel cost, but do not include fixed cost for the generation systems. For example, for diesel fuel at the price of 20¢/L and for wood with moisture at 25 percent, purchase of wood at a price less than $26/Mg will result in fuel savings. Wood at prices above $26/Mg will not provide the required fuel

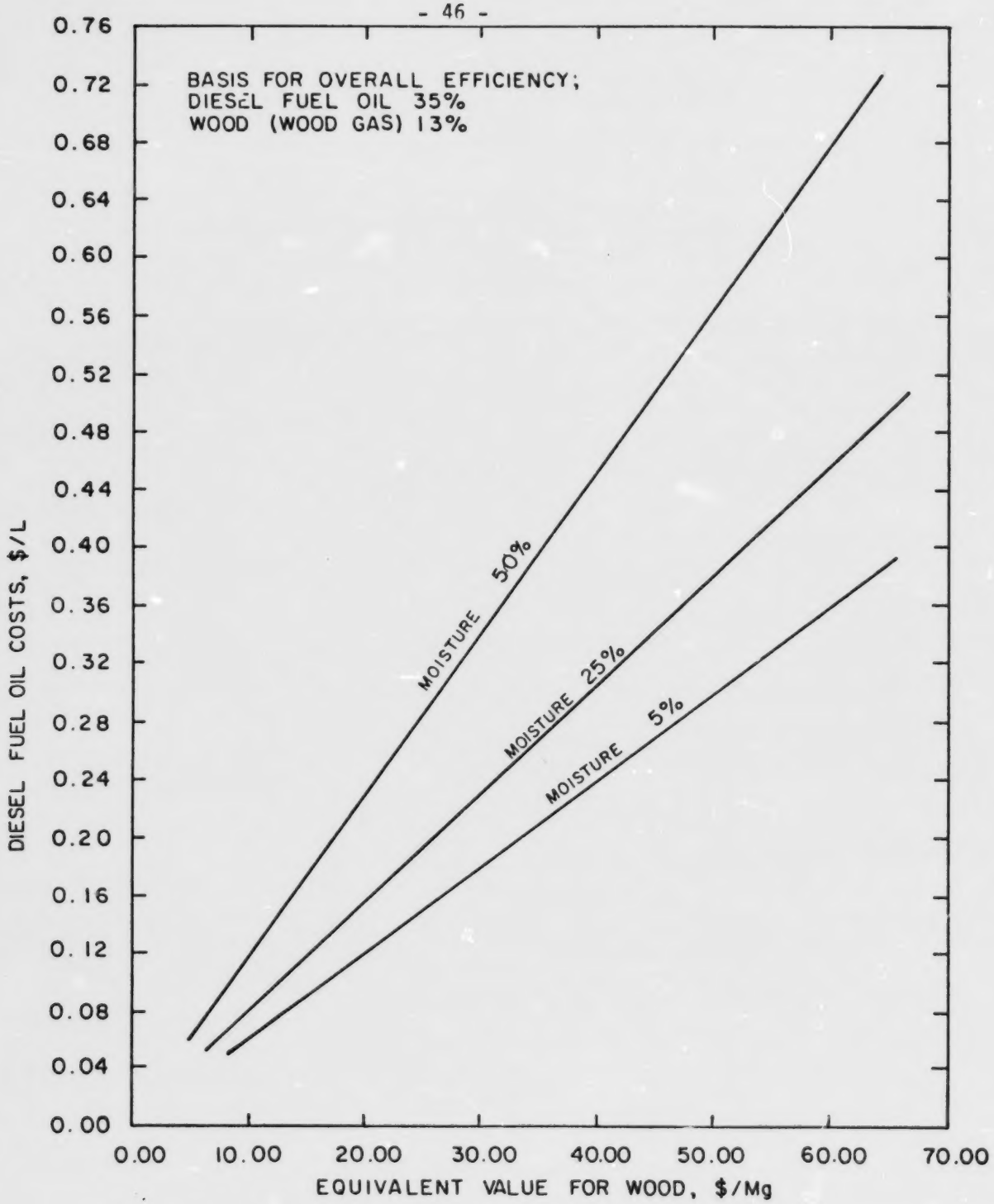

Figure 5.1. Equivalent Fuel Value of Diesel Fuel Oil and Wood at 5, 25 and 50 Percent Moisutre Content (as received basis) for Electricity Generation

savings to offset the retrofit and capital cost. Figure 5.1 is particularly useful for evaluation of the attractiveness of a fuel switch from oil to wood when frequent changes of diesel fuel prices takes place.

5.3 Cost Comparison

The main concern addressed here is the difficulty in establishing the cost of electricity from wood gas and comparison of that cost to the cost of producing electricity by conventional diesel generating systems of comparable size.

The method employed is a life-cycle costing method which is a variation of a discounted cash flow analysis.

The life-cycle cost of a particular energy system can be defined as the present value sum of all expenditures related to capital, operation and maintenance of the system over its useful life. Life-cycle cost of a system equals the sum of the capital cost plus operating and maintenance costs over the entire lifetime of the system minus residual (scrap) value at the end of the life-cycle, all expressed in dollars of a base year. By reducing all cash flows to a single figure it is possible to make cost comparisons for energy systems with different capital and operating cost profiles. Life-cycle costing is particularly useful in making the economic comparison between two systems when:

a) Economic yardsticks are required for comparing energy systems with different cost profiles, e.g. comparing systems with relatively high

front end capital costs with those characterized by high operating costs;

b) The costs of energy systems should be considered over the entire lifetime of the system;

The assumptions made for the calculations are given in Table 5.1.

The total present worth of all cash flows was calculated using the equation:

$$TPW = \sum_{t=1}^{N} \left\{ \frac{A}{(1+r)^t} + \frac{F(1+p)^{t-1}}{(1+r)^t} + \frac{O(1+q)^{t-1}}{(1+r)^t} \right\} +$$

$$\sum_{t=1}^{T^1} \frac{M}{(1+r)^t} + \sum_{t=T^1+1}^{N} \frac{M(1+q)^{t-T^1}}{(1+r)^t}$$

where:

A = amortizing interest and principal given:

$$A = C \left\{ \frac{i}{1-(1+i)^{-t}} \right\}$$

C = capital cost

i = yearly interest rate on capital

t = time (years)

r = discount rate

F = fuel cost with an escalation factor p

O = operating cost with an escalation factor q (excluding fuel cost)

M = maintenance cost with an annual growth q of maintenance cost after T^1 years

T^1 = number of years with constant maintenance cost

N = service life of the plant

Table 5.1. Assumptions Made in Cost Calculations

	Wood-Gasifier-Generator[a]	Diesel-Generator[b]
Capital Cost, C	$66,000.00	$24,000.00
Yearly Operating Costs (Labour), O Escalation on Labour	$16,000.00 10%	$ 4,000.00 10%
Yearly Maintenance Costs, M Escalation on Maintenance	$ 1,000.00 10%	$ 250.00 10%
Fuel Consumption	270 Mg/year Wood (25% moisture)	24260 L/year Diesel Fuel
Fuel Cost	--	--
Escalation on Fuel	10%	18%
Interest Rate, i	13%	13%
Discount Rate, r	16%	16%
System Efficiency	13%	35%
Electricity Production, MWh/year[c]	100 MWh/year	100 MWh/year
Residual Value	$0.00	$0.00
Service Life (Years)	15	15
Levelized Electricity Costs Based on Above Base Parameters	$0.204/kWh	$0.139/kWh

[a] Max. rated capacity 65 kVA.

[b] Max. rated capacity 92 kVA, this corresponds to equivalent engine sizes.

[c] This corresponds to a load factor of 22 percent for the gasifier and 16 percent for the electric generator.

The levelized electrical cost in constant 1981 dollars, was calculated by dividing the total present worth of all cash flows by the amount of electricity produced over the life cycle of the plant. The levelized cost for wood gasification and diesel powered generation are given in Table 5.1.

Figures 5.2 and 5.3 show the sensitivity of the levelized costs to variation in capital, maintenance, and fuel costs. In addition, the effect of load change is also depicted. In the conventional diesel generating system, the levelized electricity cost is most sensitive to fuel cost, while in the wood gasification generation system the operating cost (labour and fuel) is the main contributor to the electricity production cost. Both systems are only slightly sensitive to the maintenance cost.

The effect of load factor is more pronounced in the wood gasification generator system. Doubling of the factor results in a reduction of the levelized electricity cost by 44 percent of the base case (Figure 5.3). Figure 5.3 also shows that some increase in capital cost can be tolerated in order to reduce the operating and levelized electricity costs for the wood gasification system. To determine how large a capital expenditure is required to yield a significant overall reduction in electricity cost would require a detailed study of the engineering and operations to arrive at the optimal system design.

Varying the interest and escalation rates while maintaining an effective rate of discount at 3 percent (difference between discount and escalation) has insignificant effect on the levelized electricity cost. For example by changing the interest rate from 12 to 15 percent, the levelized costs increased by only 0.3 percent.

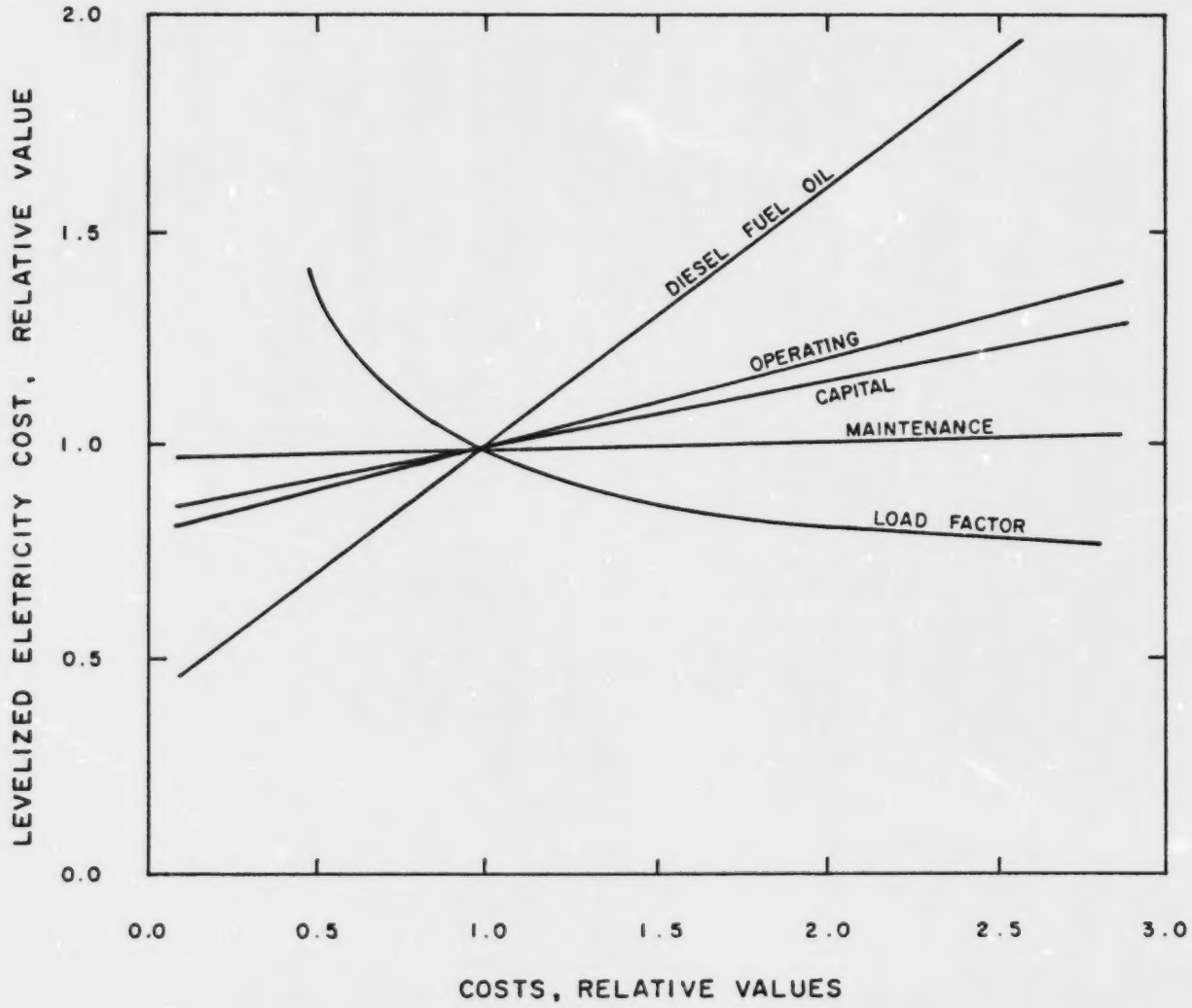

Figure 5.2. Sensitivity of the Levelized Electricity Cost to Various Key Parameters in Life-Cycle Costing for a Conventional Diesel Generating System

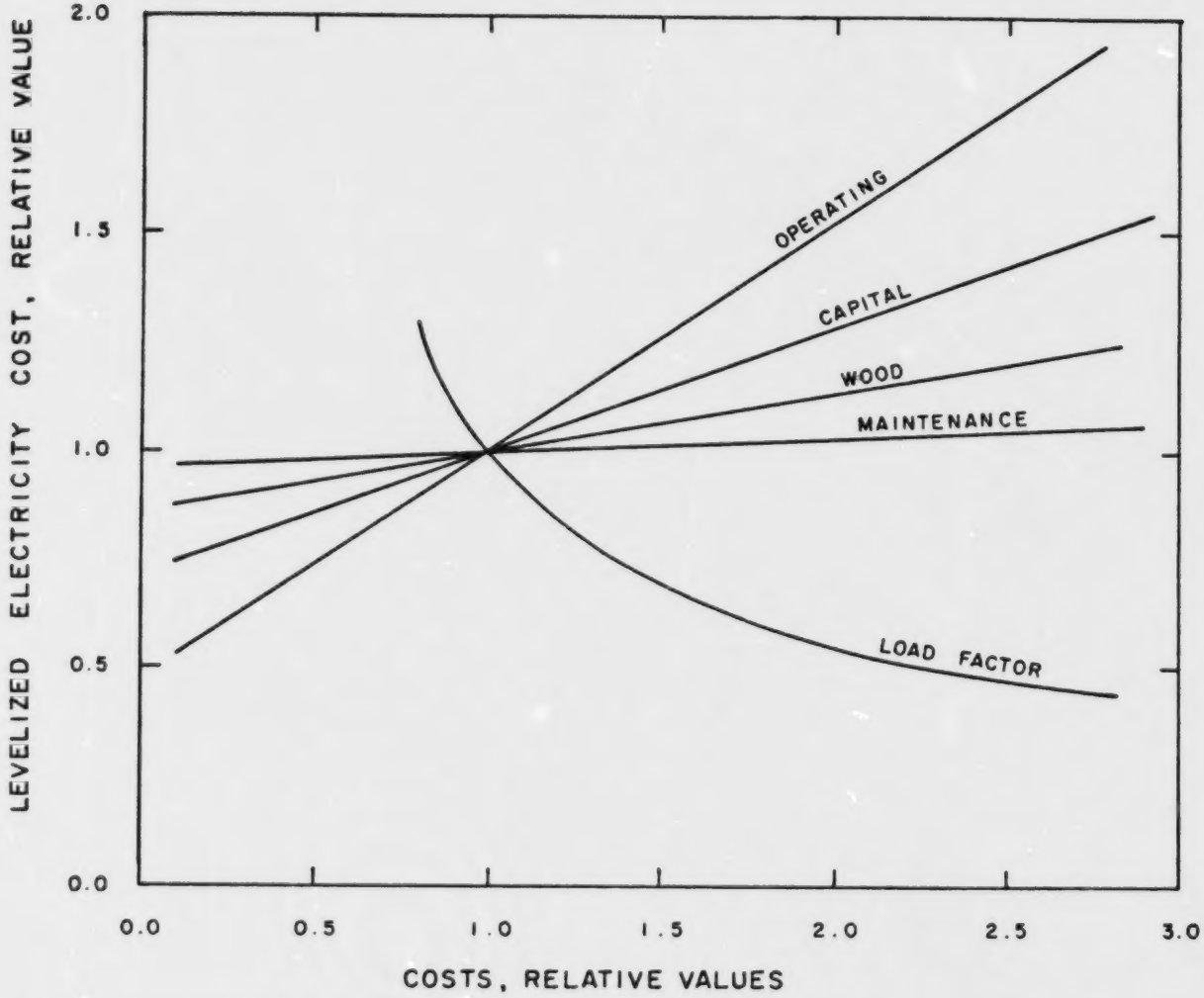

Figure 5.3. Sensitivity of the Levelized Electricity Cost to Various Key Parameters in Life-Cycle Costing for a Wood Gasifier Generating System

6. SUMMARY

Phase I of the program included the assembly and testing of the gasifier-motor-generator and preparation of the system for field trials in an isolated community. The principal observations and conclusions related to the design and operation are:

- The system performed well with the startup of the gasifier achieved in less than 3 minutes when charcoal was used in the hearth and gasification zone. Glowing, high hearth temperature was achieved immediately after lighting the gasifier.

- Several mechanical problems were identified and corrected during testing in Regina. Failure of the grate mechanism, air infiltration around the air divider, and bridging of the bed were the most serious problems.

- Typically, the gas heating value was in the range of 4.5 to 5.5 $MJ \cdot m^{-3}$. Gas composition was dependent on the hearth's temperature and was independent of the electrical load. Gas heating value remained constant over a wide range of operating conditions.

- The overall efficiency was determined from a detailed study of gas composition, gas flow rates, electricity used and wood consumed. The gasification efficiency was 75 to 80 percent which is higher than the typical efficiency of an updraft gasifier (60 - 80 percent). The engine efficiency was 20 to 25 percent which is lower than efficiency for diesel engines operating on natural gas (30 - 35 percent). The overall efficiency for conversion of wood to usable electricity was dependent on the load and

varied from 4 to 14 percent for 20 percent to 80 percent of generating capacity. At higher electrical loads, wood consumption was higher for jack pine and white spruce than for trembling aspen; however, at low loads, wood consumption was similar for all wood and the significance of this discrepancy is not clear.

- No tar or oil deposits were observed downstream of the gasifier. The scrubber and gas lines did show black deposits similar to carbon collected in the ash separator. These deposits were easy to remove by washing with water.

- At constant loads the circuit performed well, maintaining a steady current frequency. With the change of electrical load, the system responded rapidly and the frequency was stabilized within several seconds. Loss of frequency and engine stalling were experienced during refueling or when bridging of feed developed. Frequent poking and inspection of the bed partially eliminated the problem.

- Economic analysis of wood gasification vs diesel generation of electricity show the "levelized cost" over a ten year period of electricity equal to 0.204 $/kWh for wood gasification motor-generator and 0.130 $/kWh for diesel unit. A higher levy for the labor component of operating cost of wood gasification made wood gasification less attractive. However, sensitivity analyses for the key economic parameters have indicated that a significant reduction in the overall cost of electricity would be obtainable if additional automation were introduced at a moderate increase of capital cost.

The successful completion of a seven day continuous run on 1981 May 12 finalized the trial runs in Regina. A recommendation was made to transport the mobile gasifier motor-generator to a Co-op site at Jan Lake, Saskatchewan, for field testing. Phase II has started with the arrangement of transportation and of training of the Jan Lake operators. The results of the Jan Lake testing will be presented in the following report for Phase II.

APPENDIX A

Computation of Flow Through Orifice Meter

Appendix A. Computation of Flow Through Orifice Meter

The methods used for the flow calculations follow the recommendation of the A.G.A. Gas Measurement Committee Report No. 3, and are shown in Figure A1.1.

In the measurement of most gases, it is accepted practice to express the flow in L/min (or m^3/h) referred to some specified reference or base condition of pressure and temperature.* For the calculations of the quantity of gas the committee recommends the use of the formula:

$$Q = C \sqrt{h_w P_f}$$

in which

Q = quantity rate of flow at base conditions*, L/min

C = orifice flow constant

h_w = differential pressure in Pa

P_f = absolute static pressure in kPa

* The international standard ISO 5024 - Petroleum Liquids and Gases - Measurement - Standard reference conditions reads as follows:

"The standard reference conditions of pressure and temperature for use in measurement on crude petroleum and its products, both liquid and gaseous, shall be 101.325 kPa and 15°C, with the exception of liquid hydrocarbons having a vapour pressure greater than atmospheric at 15°C, in which case the standard pressure shall be equilibrium pressure at 15°C".

It should be noted that several temperature bases other than 15°C are in use. Even in the Gas Industry of the metric countries in the Western Hemisphere, where the 15°C reference temperature has been adopted almost universally in the gas supply contracts, 0°C reference conditions are still used internally in many gas distribution operations. Also it should be kept in mind that the temperature in the "standard temperature and pressure" (abbreviation STP) found in many chemistry and physics books refers to 0°C.

Several organizations in various parts of the world have proposed rationalization of the pressure base and are working at achieving acceptance of 100 kPa as a replacement for 101.325 kPa. Throughout this work the ISO 5024 standard will be adhered to.

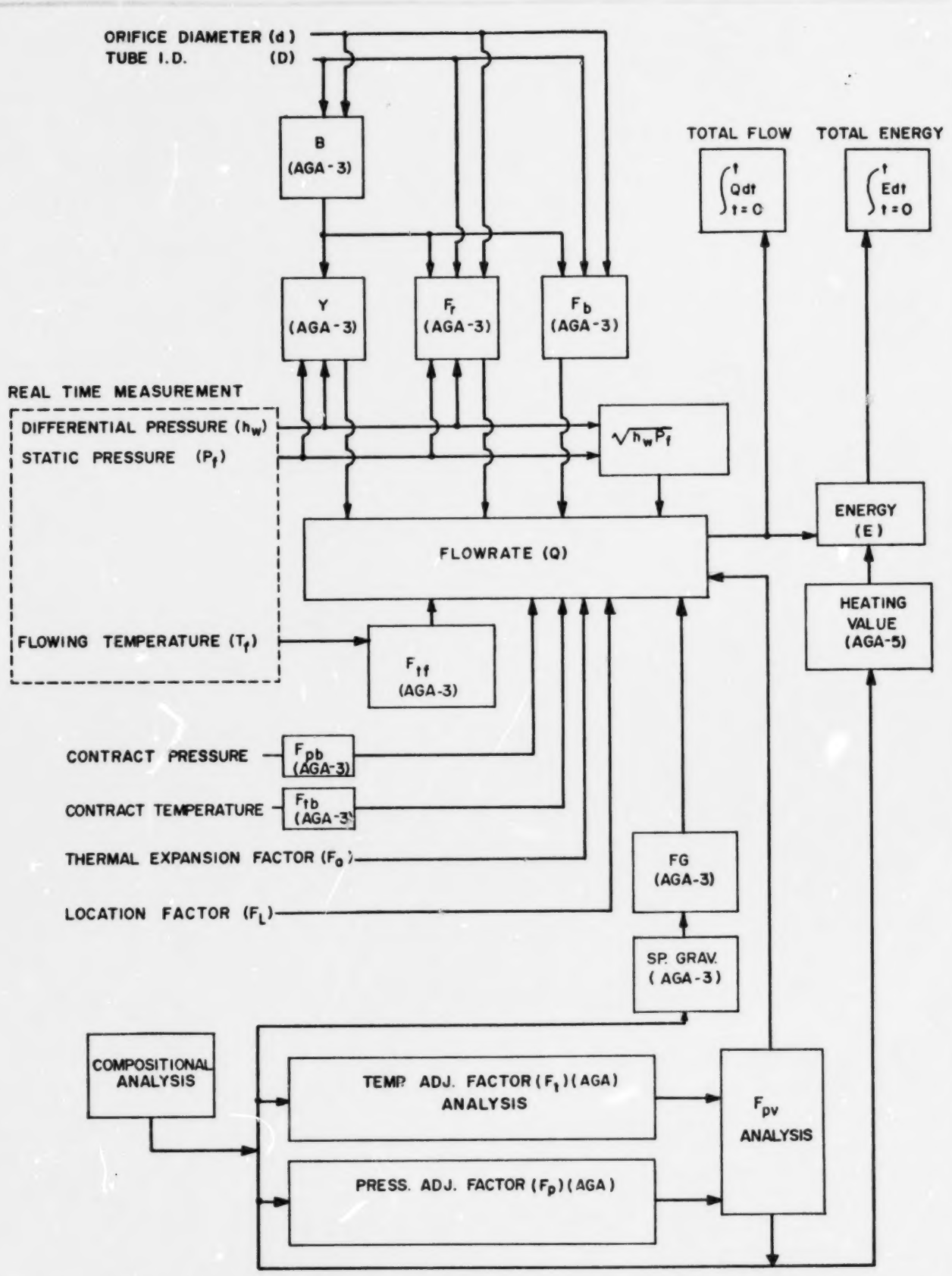

Figure A.1. Flow Diagram Showing Methods Used in Gas Flowrate Measurements

The orifice flow constant C^1 may be defined as the rate of flow in litres per minute, at base conditions where the extension $\sqrt{h_w P_f}$ equals one. It is to be calculated by the equation:

$$C^1 = F_b \, F_r \, Y \, F_{pb} \, F_{tb} \, F_{tf} \, F_g \, F_{pv} \, F_m$$

in which:

F_b = basic orifice factor

F_r = Reynolds number factor

Y = expansion factor

F_{pb} = pressure lease factor

F_{tf} = flowing temperature factor

F_{tb} = temperature base factor

F_g = specific gravity factor

F_{pv} = supercompressibility factor

F_m = manometer factor

The basic orifice factor F_b is taken from Table 8 in the AGA report for the correction for orifice and pipe size. The Reynolds factor F_r is obtained using Table 9 in the report. The average value of $h_w P_f$ used in calculating F_r was obtained from preliminary runs. The expansion factor Y is taken from Table 11 of the committee report and depends on the tap location from which the static pressure is taken. Here the ratio h_w/P_f is an index with which the value of Y is selected. Here, as well as for the previous factor, variations from the average h_w/P_f will be compensating. The pressure base factor and temperature base factor are used to change to non-standard pressure and temperature bases respectively. The flowing temperature factor is based on the actual flowing temperature, and was calculated from the

temperature of the gas. The specific gravity factor is normally based on the actual specific gravity of the gas and this factor was approximated as follows:

The CO_2, CO and CH_4 concentration in the gas were determined using on-line Riken IR-550 Infrared analyzers. The hydrogen concentration was approximated and assumed to be equal to the carbon monoxide concentration. By assuming saturation of the gas with water vapour the amount of water in the gas was calculated from the gas temperature. A value for the nitrogen concentration was then obtained from: $\%V_{N_2} = 100 - \%V_{CO_2} - \%V_{CO} - \%V_{CH_4} - \%V_{H_2}$. Using the density of the pure components the specific gravity for the gas mixture was then calculated. Since the specific gravity factor is expressed as $F_g = \frac{1}{\sqrt{SG}}$ the effect of differences in gas composition are small. With the exception of the factors F_r, Y and F_g all factors are constants. However, even F_r and Y vary only slightly with large changes in h_w and P_f and are well within the error limits of such parameters as the fuel moisture content and fuel weight.

Table A1.1. F_r AND Y WITH CHANGES IN STATIC AND DIFFERENTIAL PRESSURES

h_w = 402 Pa, P_f = 83.23 kPa	F_r = 1.0109
	Y = 0.9996
h_w = 126 Pa, P_f = 94.23 kPa	F_r = 1.0089
	Y = 0.9984

APPENDIX B

Description of Test Runs

Appendix B. Description of Test Runs

The following is a brief description of each of the controlled test runs. Data for run duration, wood consumption and the amount of electricity generated are given in Table 3.1.

Run 45JP-01

The engine started at the first attempt, three minutes after lighting the gasifier, and an electrical load of 45 kW was applied to the generator in 15 kW increments.

After approximately 2 hours the rotational speed suddenly dropped and the electrical load was reduced to 30 kW. One minute later the engine stopped and could not be restarted. Both the inner doors and the top lid of the reactor were opened and the wood poked down with a poke rod. The wood level in the reactor dropped significantly indicating serious bridging above the gasification zone.

The engine was restarted and a bucket of wood chips dumped in the reactor before reapplying the electrical load to the generator.

At the end of this run a nipple with removable cap was built into the top lid to allow poking during operation. The practice was established to poke before each fueling cycle, and when the engine line frequency dropped below 55 Hz.

Run 30JP-02

For the duration of this run a 30 kW electrical load was applied to the generator. Using the poke hole in the top lid of the wood hopper the wood was poked down before each addition of fresh wood chips. It was observed that in most cases the wood chips tended to jam in the fuel hopper rather than further down in the reactor. After two hours of continuous operation the line frequency suddenly dropped below 55 Hz, and the electrical load was reduced by 5 kW. The wood was then poked down and the electrical load increased to 30 kW. During the remainder of the test the line frequency varied only from 59-1/2 to 60-1/2 Hz, as was observed during the first two hours of the test.

Run 15JP-03

Before starting this run the orifice plate in the gas supply line was cleaned. The orifice plate was extremely dirty, because the scrubber-cooler pump was not working during the previous two runs.

There is no flow indicator in the scrubber lines and the scrubber pump failure was suspected after the cork demister fouled.

A 15 kW electrical load was applied throughout this run, and the line frequency stabilized around 61 Hz. Adjustments to the air to gas ratio on the engine carburetor could not lower this frequency.

Three times during refueling, the engine slowed resulting in a line frequency drop below 55 Hz. The frequency also dropped on a few occassions during poking.

During one fueling cycle the drive chain for the bucket elevator broke. The chain was fixed without shutdown and the gasifier was refueled manually using a garbage pail.

Run 45JP-04

A 45 kW electrical load was established within minutes after lighting the gasifier. There was an occasional drop in line frequency during poking just before adding additional wood chips, however, the frequency did not drop below 55 Hz.

The seal around the bottom ash door seemed to be leaking and this was confirmed when the ash was removed the next day. Usually the ash is black and contains approximately 50 percent carbon, in this case the ash was white as the carbon was combusted by the air leaking in around the ash door.

Run 30JP-05

Within minutes after startup the engine slowed and stalled when an electrical load of 15 kW was applied. The wood was poked down and the engine restarted. The engine stalled two more times during the first 40 minutes under an electrical load of 30 kW. In both cases the engine was restarted without prior poking. A too rich or too lean setting for the gas/air mixture on the carburetor may have been the problem. The system performed well during the remainder of the test with the line frequency only once dropping below 55 Hz during a refueling operation.

Run 15JP-06

Again the engine was started 3 minutes after lighting the gasifier, and a 15 kW electrical load was established. The gasifier performed well and no irregularities were observed. Only once did the line frequency drop below 55 Hz during poking. During the run the line frequency remained a steady 61 Hz. Again as in run 15JP-03 the frequency could not be lowered further by adjusting the gas to air ratio on the carburetor.

Run 05JP-07

The system required two restarts as a result of bridging inside the gasifier; usually the wood bridges in the wood hopper. After one hour of operation under a 15 kW electrical load, one of the thermocouples attached to the outer jacket near the air distribution box indicated an abnormally high temperature. The grate mechanism was switched to continuous operation to decrease the pressure drop across the char/ash bed below the hearth. After 15 minutes the reactor started to glow red hot on the front near the air inlet. The run was then aborted to prevent damage to the gasifier.

The reactor was emptied after cooling down overnight and reloaded with fresh charcoal. The ash/char below the bed was severely plugged and caused the large pressure drop.

The gasket between the outer jackets and the air distribution box was replaced.

Run VJP-08

During this run the electrical load was varied to test gasifier response. The engine again was started three minutes after lighting the gasifier and a 5 kW electrical load was applied to the generator. The electrical load was increased to 15 kW after 15 minutes. The electrical load was then stepped up to 35 kW. Poking before refueling never resulted in a line frequency drop of more than 1 Hz. Shortly after the electrical load was lowered from 35 kW to 15 kW the engine suddenly stopped. Poking indicated bridging inside the reactor. The engine was restarted but a 45 kW load could not be maintained without the line frequency dropping below 50 Hz. The maximum load that could be applied was 35 kW. The engine stopped once more and was restarted without poking.

The system reacted well to sudden load changes and recovery was usually within 2 to 3 seconds. Changes from 35 kW to no load and back to 35 kW were handled very well, with the tendency of the line frequency being to rise above 65 Hz at no load.

Run 15JP-09

A 35 kW electrical load was applied within three minutes after lighting the reactor. Nine minutes into the test the static gas pressure suddenly dropped to 78.2 kPa and the engine slowed down and stalled. The engine was immediately restarted and a reduced load of 15 kW applied. The engine maintained its speed and the line frequency was a stable 61 Hz. The static gas pressure remained low indicating plugging below the hearth or in the gas

cleaning system. Switching to continuous grate drive did not correct the problem. The system maintained constant load and frequency for three hours until the engine suddenly stopped after a refueling operation. The engine was restarted and ran well throughout the remainder of the test.

During one of the refueling operations too much air was mixed in with the gas and after closing the top lid a minor explosion took place. These types of explosions have occurred earlier and resulted in a lifting of the relief flaps combined with a hissing sound when excess gas and wood chips are blown off the top rim of the gasifier. No effect is noticed on the engine and no damage has occurred so far.

After cooling down and unloading, it was observed that the wiper arm below the grate did not move, and further investigations revealed that the grate mechanism did not work.

Run 05JP-10

The gasifier was difficult to light and this was most likely caused by adding insufficient charcoal after reloading the gasifier. The gasifier was emptied and reloaded after the discovery that the grate mechanism did not function properly. The engine could be started after 25 minutes, when sufficient charcoal was generated from the blast supplied by the startup fan. The pressure drop across the char/ash bed slowly increased during the run.

This was the first of the scheduled test runs during which the engine did not stall and the line frequency did not noticeably drop.

Run 30JP-11

The engine was started four minutes after lighting the gasifier and a 30 kW electrical load was applied. The engine slowed markedly after approximately 20 minutes as a result of a rapid decrease in static pressure. The electrical load was removed but the engine stalled shortly afterwards. The engine was restarted after poking but could not maintain an electrical load of 20 kW. After an additional 16 minutes the run was aborted. The total elapsed time from lighting the gasifier was 130 minutes.

Run 30JP-12

The gasifier was emptied after cooling down and reloaded. A 30 kW electrical load was applied 17 minutes after lighting the gasifier but the load had to be reduced by 5 kW in order to maintain 1800 revolutions per minute (60 Hz). The gasifier was refueled and the load increased to 30 kW. Several times during the next hour the engine speed dropped, resulting in the line frequency dropping below 55 Hz. In each case the engine speed was increased by decreasing the applied electrical load by 5 kW. Because a steady load could not be maintained the run was terminated after approximately 3 hours. After cooling down, the reactor was emptied but the char bed below the hearth showed no signs of severe plugging. Also the grate drive mechanism seemed to be functioning properly. The problem was diagnosed as severe fouling of the flow straightening vanes located ahead of the orifice meter in the gas supply line.

Run 15JP-13

The gasifier was started but the gas pressure was still low. The static gas pressure was 83.4 kPa at a 15 kW electrical load. The run was aborted 16 minutes after startup. The problem was diagnosed as severe plugging below the hearth, as a result of the non-functioning grate drive. Proper functioning of the grate drive can only be observed through the ash door and can therefore only be monitored when the gasifier is not operating.

Run 15JP-14

This was the only run during which the engine could not be started. The problem was identified as improper loading of the gasifier with insufficient active charcoal at the hearth level. After approximately 50 minutes the batteries were drained by prolonged running of the startup fan which is powered by the engine batteries. The batteries were recharged overnight.

Run VJP-15

The gasifier was lit and the engine started within minutes. An electrical load of 30 kW was applied and two minutes later increased to 45 kW. Another two minutes later the electric load was further increased to 60 kW. Under this load the generator is overloaded by 15 percent over the rated capacity. The system was not able to maintain the proper frequency and stabilized around 55 Hz (approximately 1650 revolutions per minute). To test the performance the gasifier was refueled under this load. The gasifier is less sensitive to false air being drawn into the gasifier from the top during refueling under

high load. A 55 kW load could be maintained without problems. The electrical load was reduced to 50 kW and 90 minutes later the engine suddenly stalled. After restarting the largest electrical load that could be applied without causing a permanent loss of frequency was 35 kW.

During the remainder of the test the engine stalled two additional times without prior drop in rotational speed.

Inspection after cooling down revealed that the grate mechanism had failed once more.

Run 20JP-16 and 30WS-16

The engine would not start and the problem was diagnosed as a broken wire in the electronic ignition system.

For this test the reactor at the start contained mainly jack pine and was refueled with white spruce. After running for 90 minutes and the addition of 51 kg of white spruce the engine was stopped when the inner hopper doors could be closed. A reading was taken from the kWh meters and the engine was restarted. The electrical load was increased to 30 kW, and the unit only stalled once at which point it was immediately restarted and the 30 kW load reapplied.

Run 20WS-17

The engine could be started only after several attempts and a 20 kW electrical load was applied. After 15 minutes of operating under this load

the static gas pressure steadily decreased to 78.2 kPa and the engine suddenly stalled. The engine was restarted and the electrical load reapplied.

During the remainder of this test the engine stalled three more times, once just after the addition of another charge of wood chips to the gasifier.

Run 10WS-18

Startup was achieved within a few minutes and a 10 kW load was applied. This test was different from all previous runs in that after approximately 3 hours the engine rotational speed suddenly increased, causing the line frequency to rise to 63 Hz. The frequency was reduced to 60 Hz by adjusting the gas to air ratio.

The engine stalled three times during this test.

Run 40WS-19

Startup was normal and a 40 kW electrical load was applied. Within the first 60 minutes the engine stalled 3 times. During the remainder of the test it was difficult to prevent the system from stalling and on several occasions the electrical load had to be reduced to 35 kW, to prevent the engine from stalling and to allow the engine to regain 1800 revolutions per minute (60 Hz).

However, it was observed that hardly any wood chips jammed in the hopper, and that less poking was required. Several times after refueling the

frequency dropped and the engine would not regain speed without temporarily lowering the electrical load by 5 kW.

Run 40TA-20

The engine was started and a 50 kW electrical load applied within minutes after lighting the gasifier. After 5 minutes the load was reduced to 45 kW. Sixty minutes later the load had to be reduced further to 40 kW, to be able to maintain 60 Hz line frequency.

The engine stalled only once after 5 hours of operation, and less poking was required as compared to tests using jack pine as fuel.

Run 35TA-21

Again no problems were encountered in starting the engine within minutes after lighting the gasifier, and almost immediately a 35 kW electrical load was applied to the generator. The unit performed well with the line frequency deviating markedly from 60 Hz only once. The unit recovered immediately on its own without the need for momentarily reducing the electrical load.

Run 20TA-22

A 20 kW electrical load was applied immediately after startup. Fifty minutes later the engine suddenly stalled; the engine was restarted and the test continued. Three hours after startup one of the skin mounted thermocouples on the outer jacket of the gasifier registered a higher than usual temperature and the reactor started to glow shortly afterwards on a spot

to the right and above the air inlet. The unit was kept operating while closely monitoring the hot spot. The spot cooled to slightly above normal after 30 minutes, but after an additional 30 minutes started to glow again. The glow did not disappear until the test was terminated two hours later.

Run 10TA-23

During the previous runs no scrubber water was being discharged, and the assumption was made that most of the water did not condense because of the high scrubber water temperatures reached during the test. In addition the water level in the scrubber did not rise noticeably during these tests. However, the unit could not be started and after several attempts it was realized that the water level in the scrubber was too high and the startup fan could not overcome the pressure drop. After the water level in the scrubber had been lowered the engine could be started without problems.

The engine did not stall during this test and only once did the rotational speed drop.

At one point during the test a wood chip was discovered jammed under the lid causing false air to be drawn into the gasifier via the fuel hopper.

During one additional run the breakers for the grate drive motor tripped. The reactor was emptied and reloaded. The unit was operated successfully for 8 hours at 35 kW electrical load. The next day the pressure drop across the char/ash lid below the grate was so large that the engine could not maintain a rotational speed of 1800 revolutions per minute, even without an electrical load being applied. The unit was shut down and emptied after cooling. In

previous problems with the grate a pin connecting the main bevel gear to the drive shaft broke and was replaced on several occasions. This time the drive shaft broke at the location of the pin as a result of excessive manual force. Even when the grate drive is broken down the unit is operable under a reduced load since the tumbler on the main drive shaft will still lift a corner of the grate. However, the grate was warped to such an extent that the drive shaft tumbler could move freely below the grate without lifting. In this case no ash was removed from the charcoal bed.

APPENDIX C

Graphical Presentation of the Variations of
CO, CO_2, CH_4 and the Hearth Zone
Temperatures During Several Test Runs

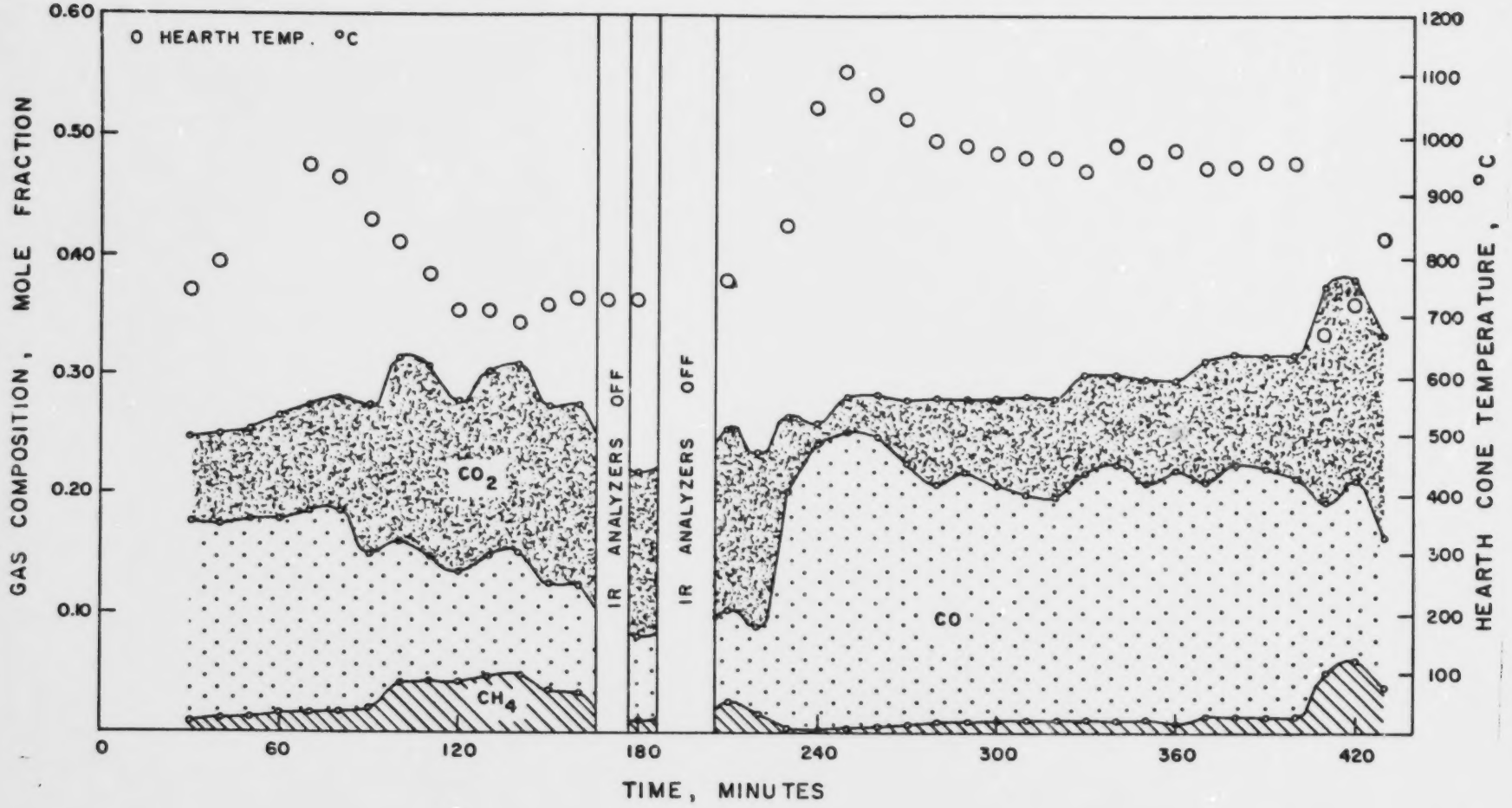

Figure C.1. Gas Composition and Temperature Profile Run 45JP-01

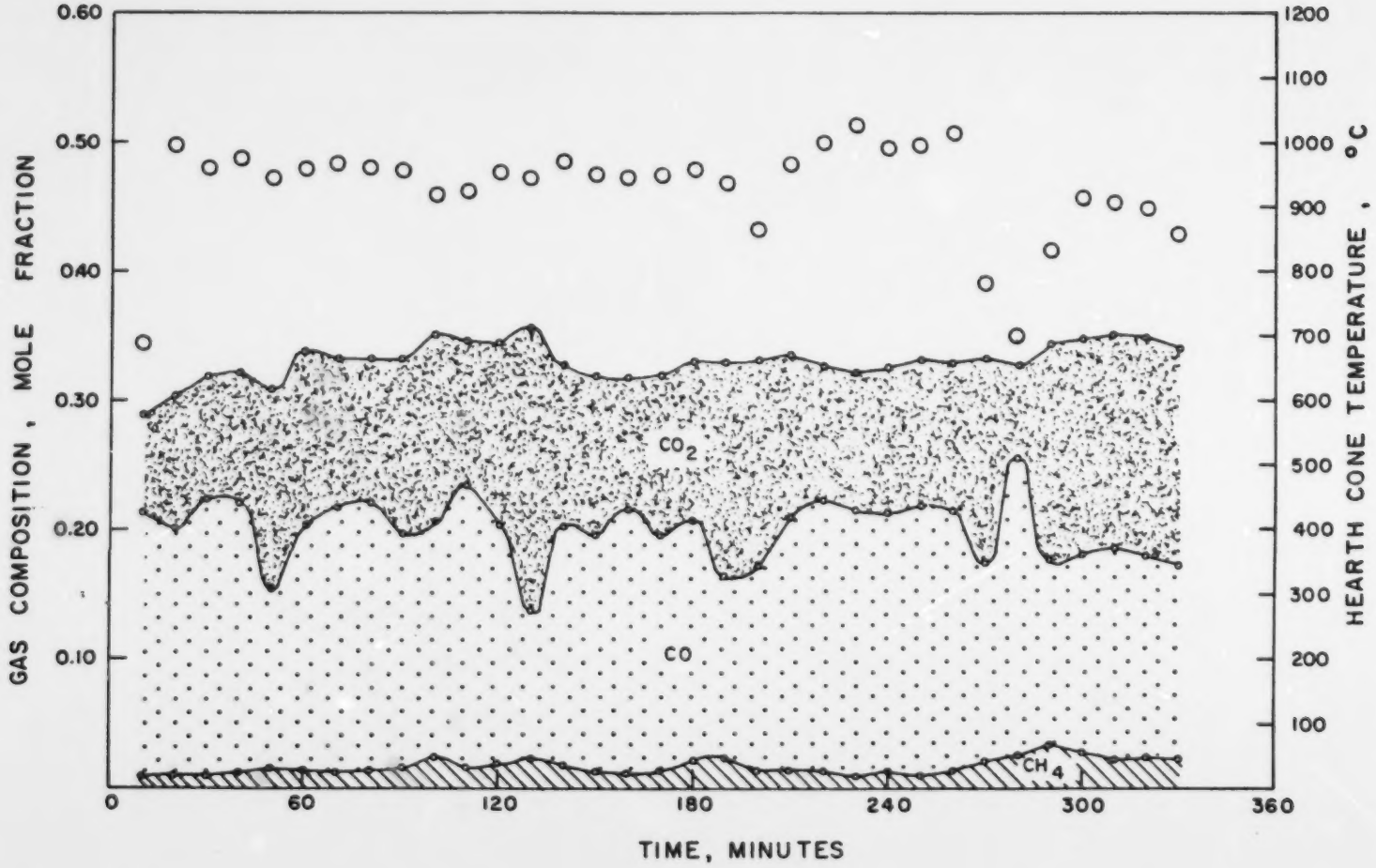

Figure C.2. Gas Composition and Temperature Profile Run 45JP-04

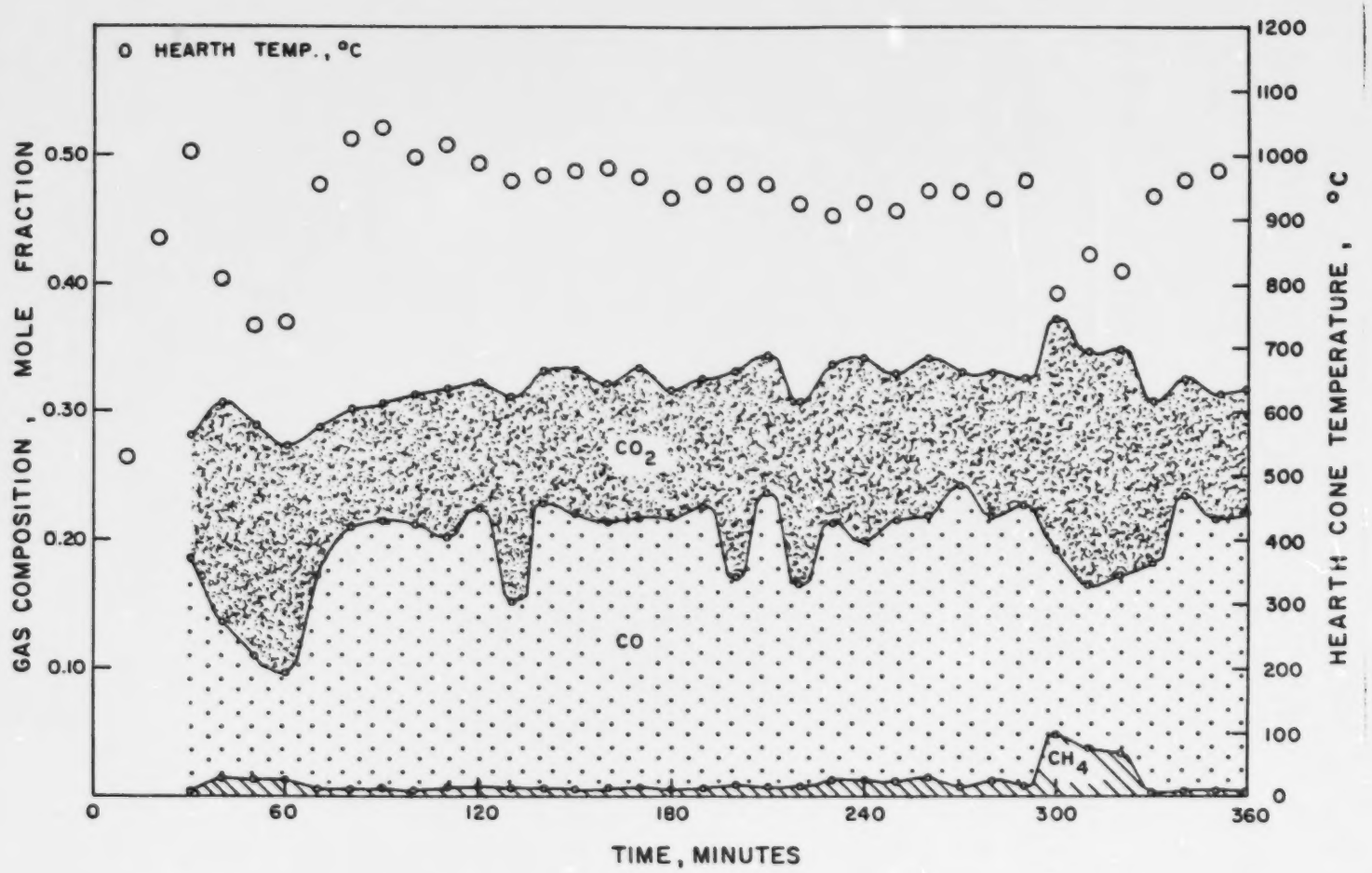

Figure C.3. Gas Composition and Temperature Profile Run 30JP-05

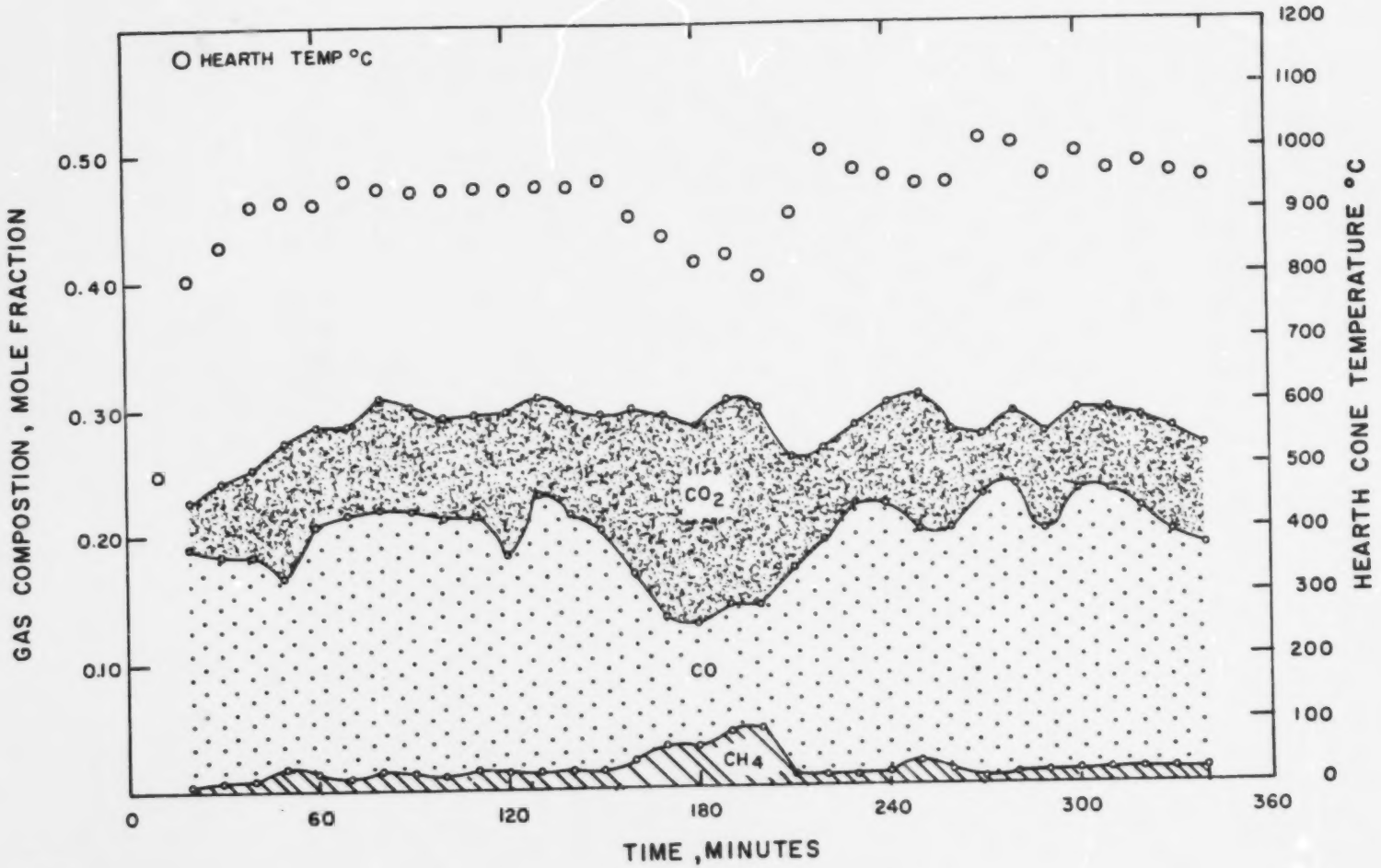

Figure C.4. Gas Composition and Temperature Profile Run 15JP-09

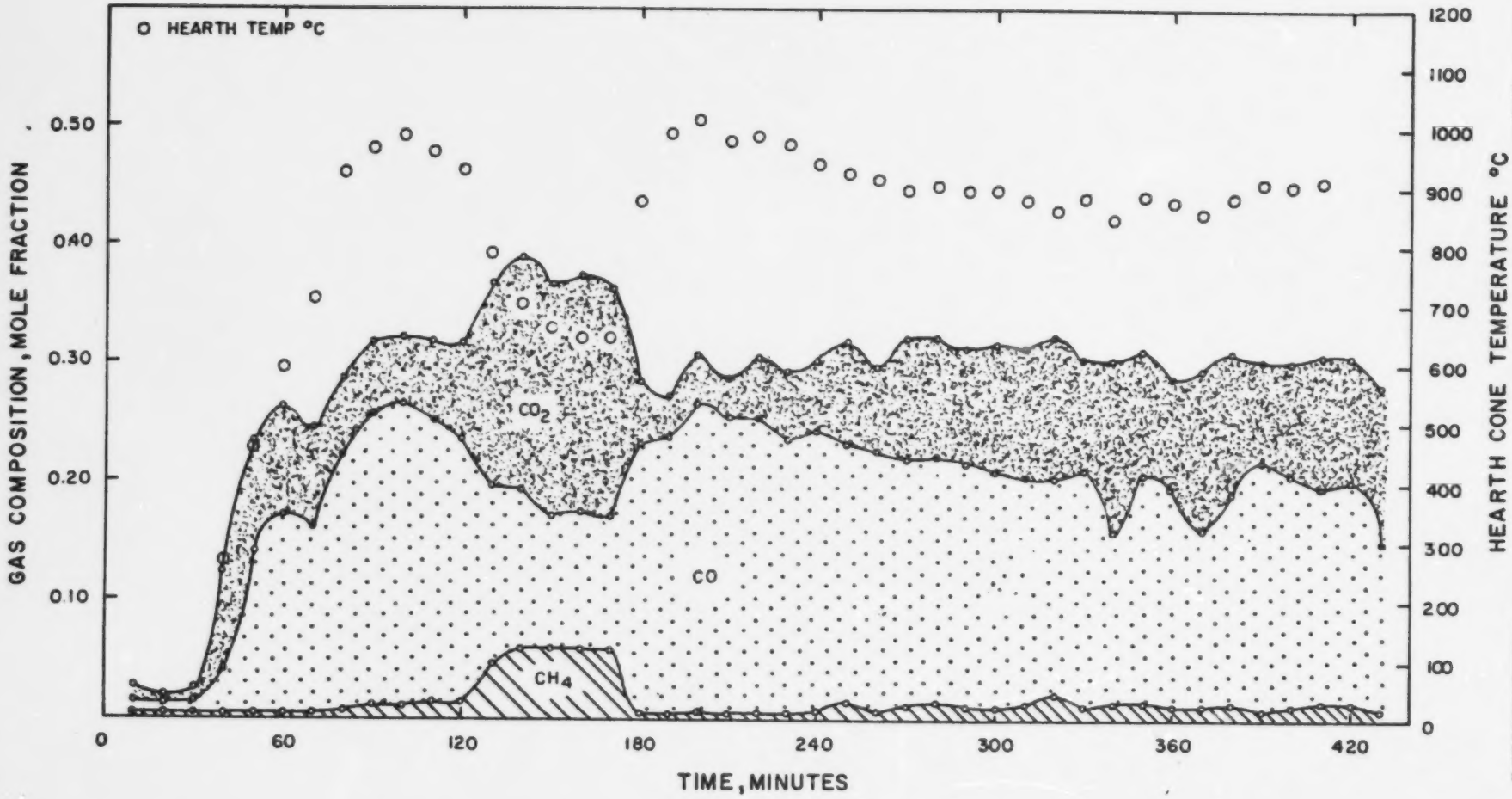

Figure C.5. Gas Composition and Temperature Profile Run 05JP-10

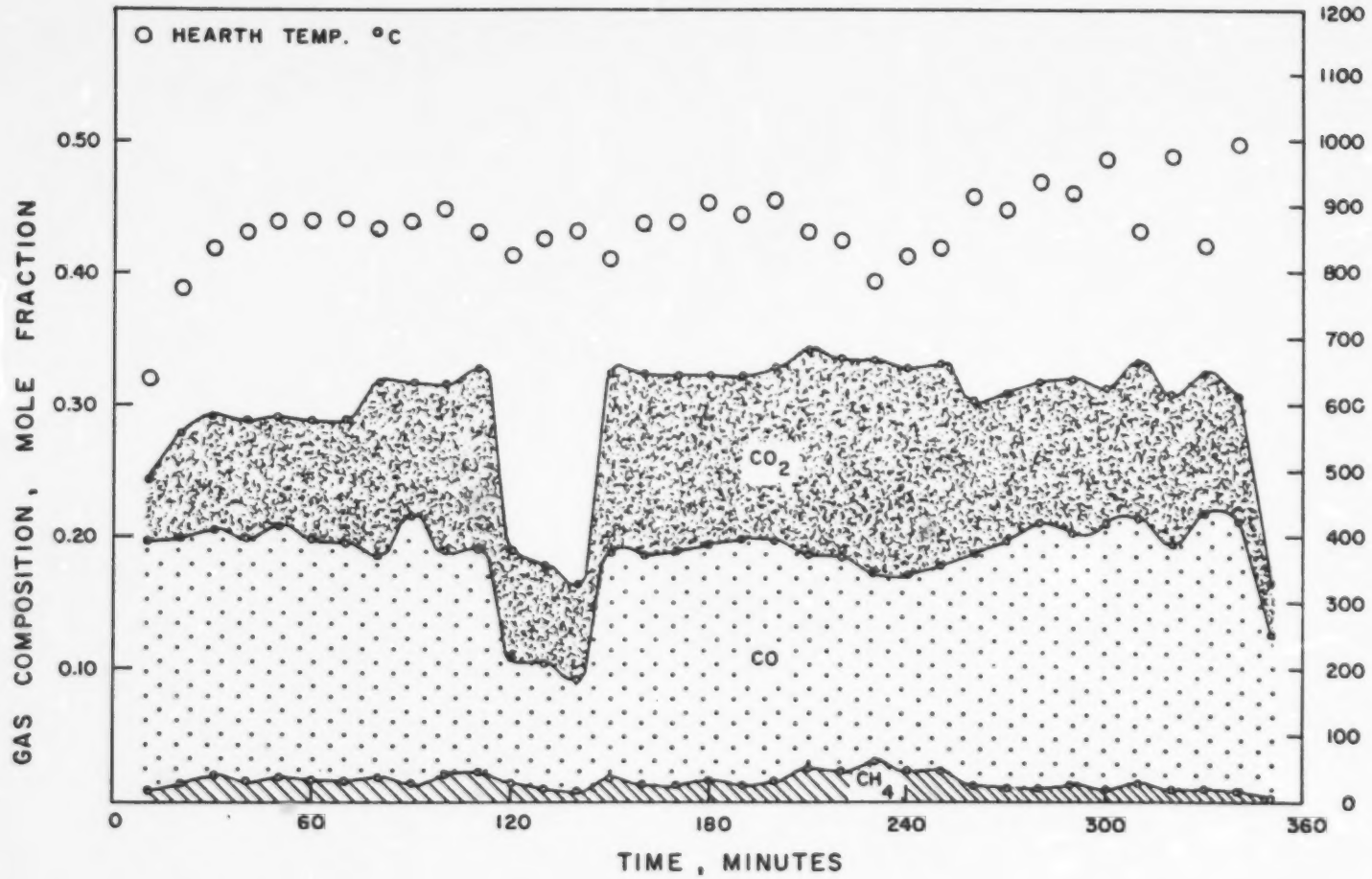

Figure C.6. Gas Composition and Temperature Profile Run VJP-15

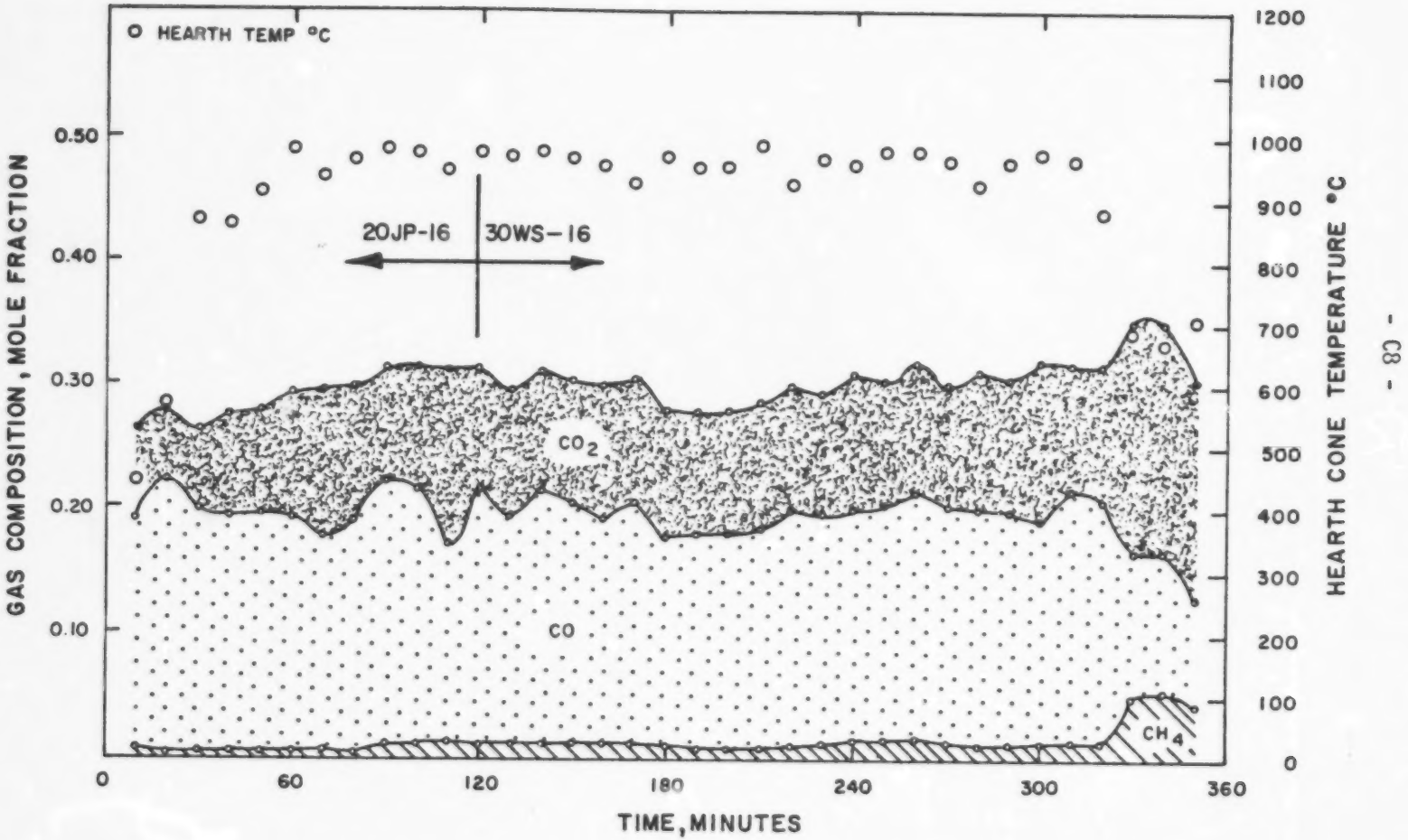

Figure C.7. Gas Composition and Temperature Profile Run 20JP-16; 30WS-16

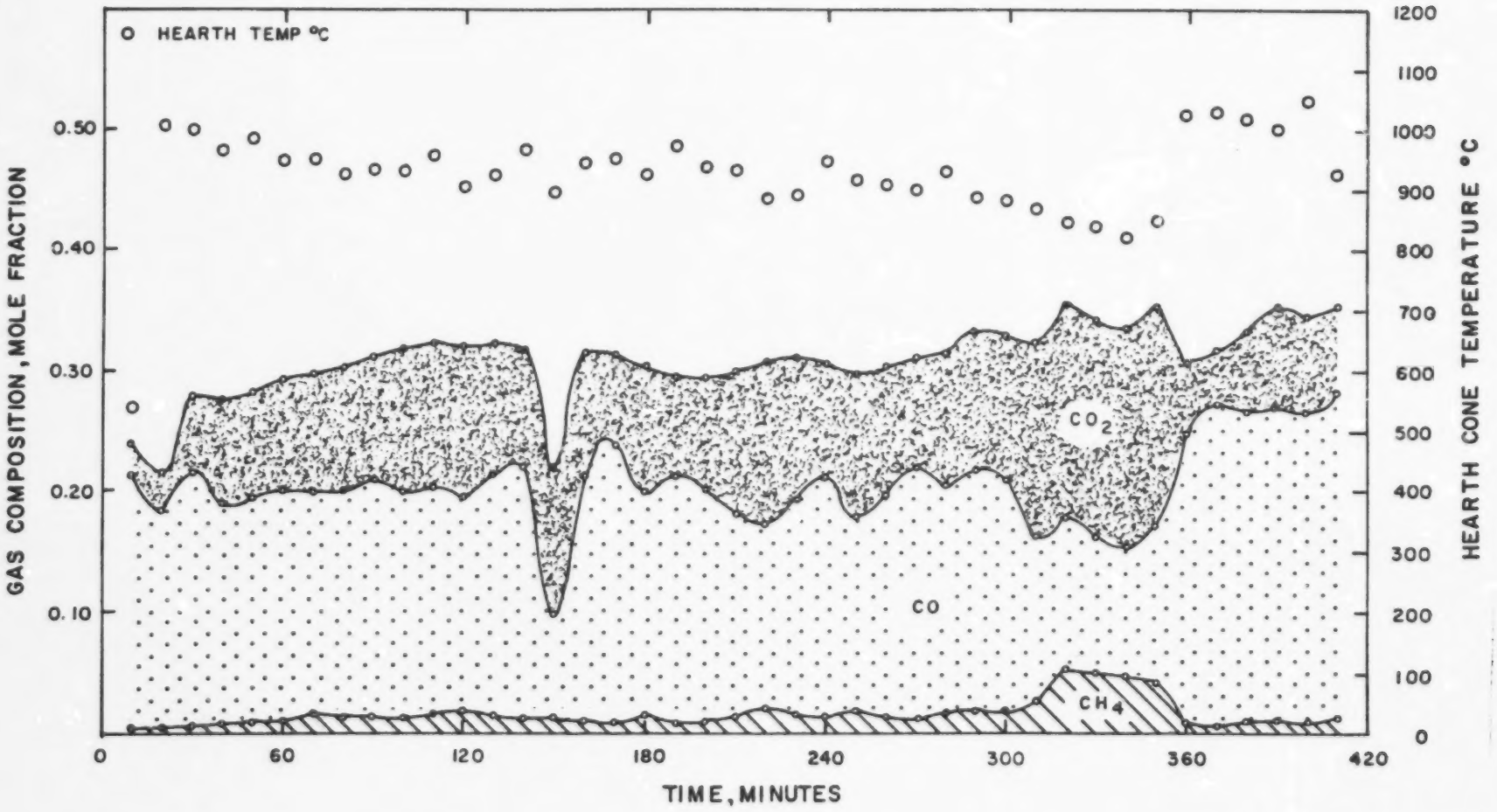

Figure C.8. Gas Composition and Temperature Profile Run 20WS-17

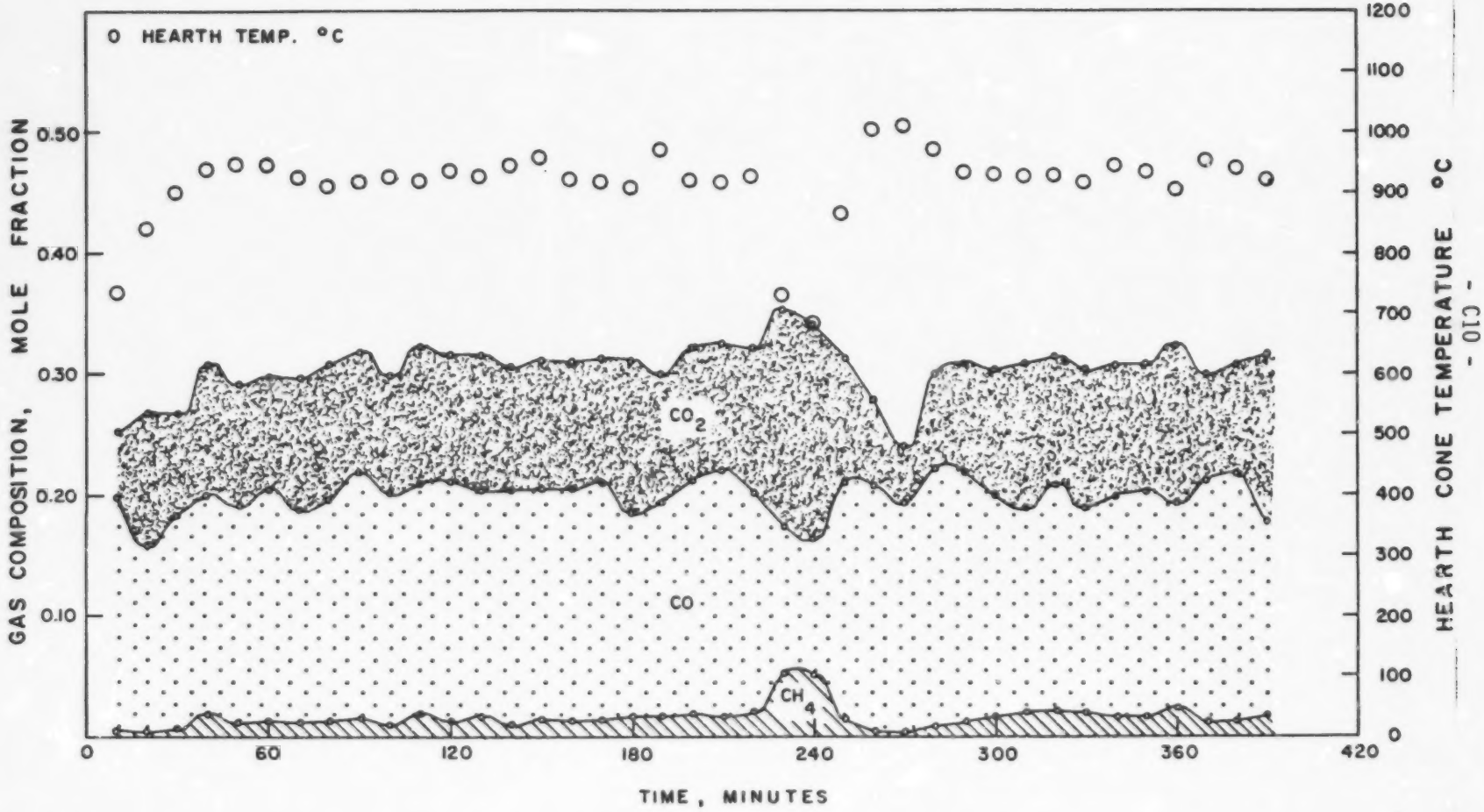

Figure C.9. Gas Composition and Temperature Profile Run 10WS-18

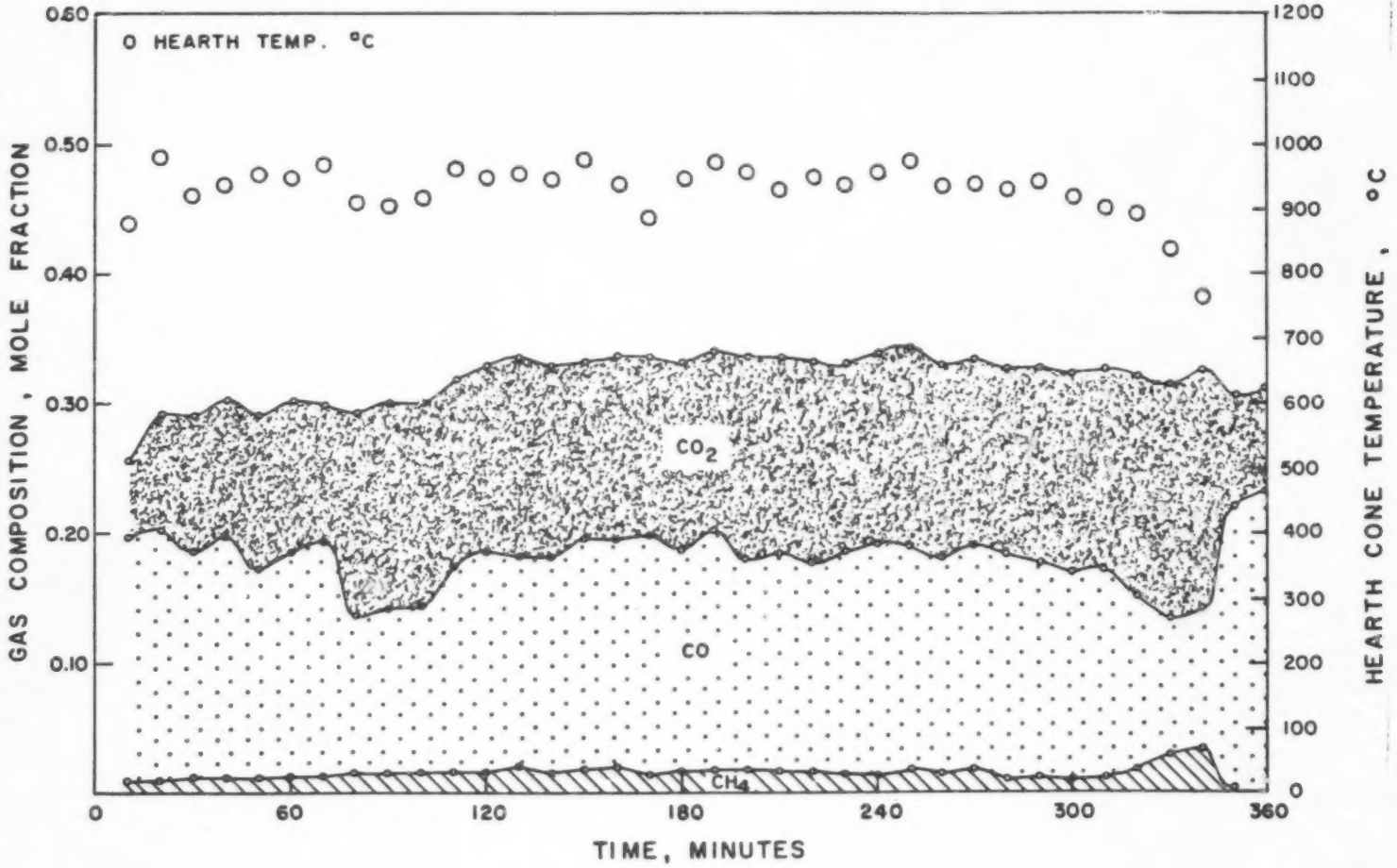

Figure C.10. Gas Composition and Temperature Profile Run 40WS-19

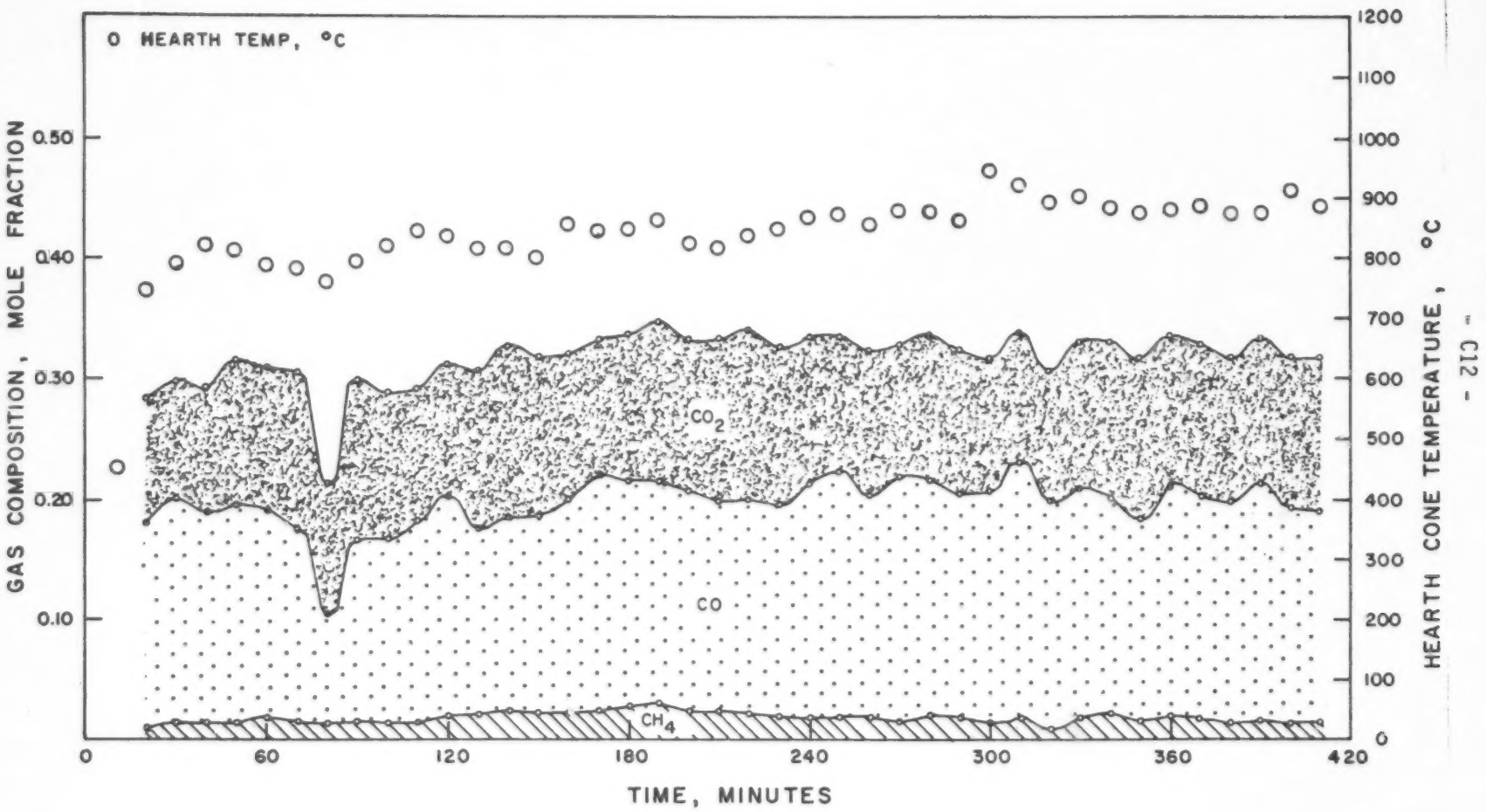

Figure C.11. Gas Composition and Temperature Profile Run 40TA-20

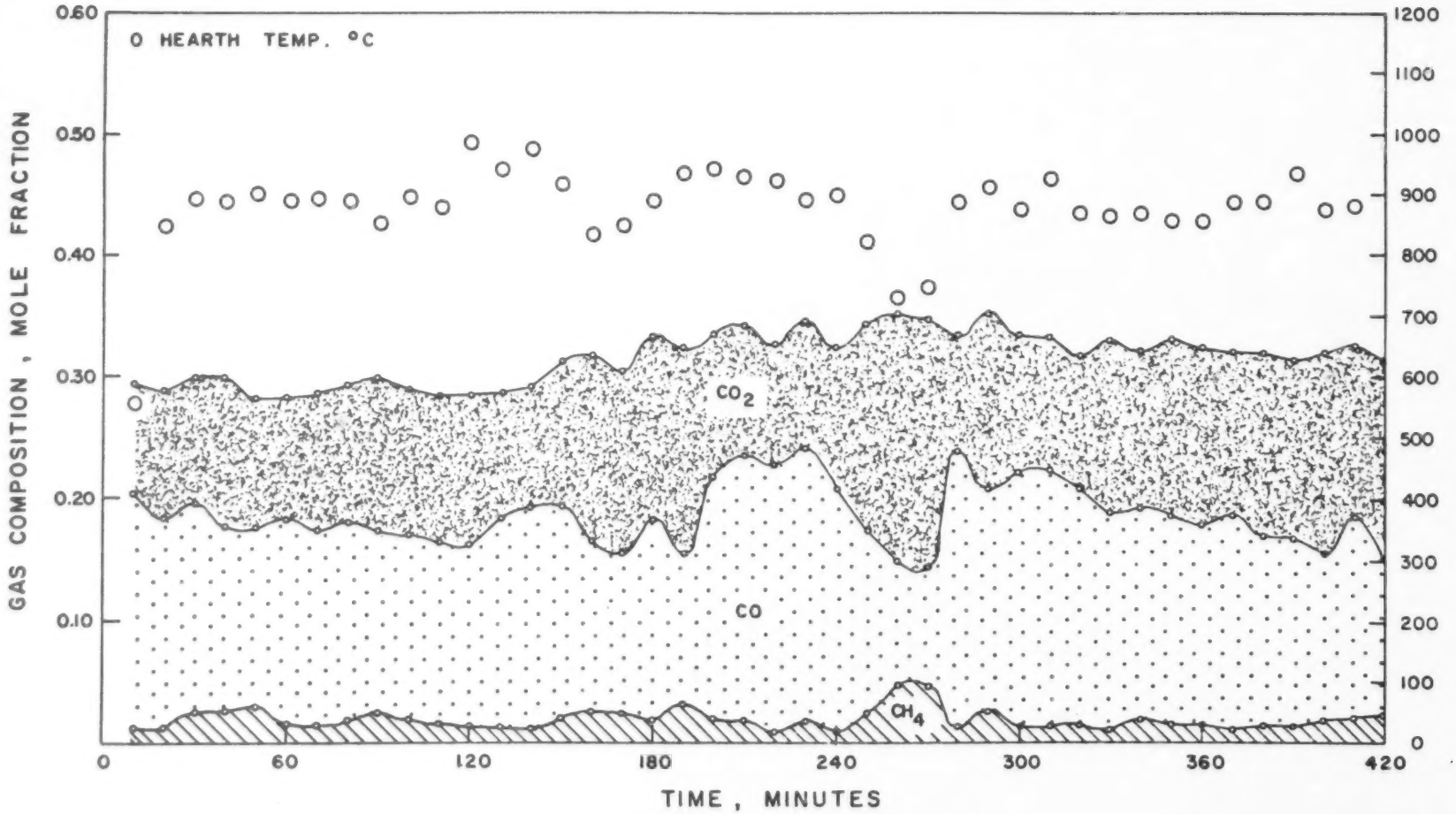

Figure C.12. Gas Composition and Temperature Profile Run 35TA-21

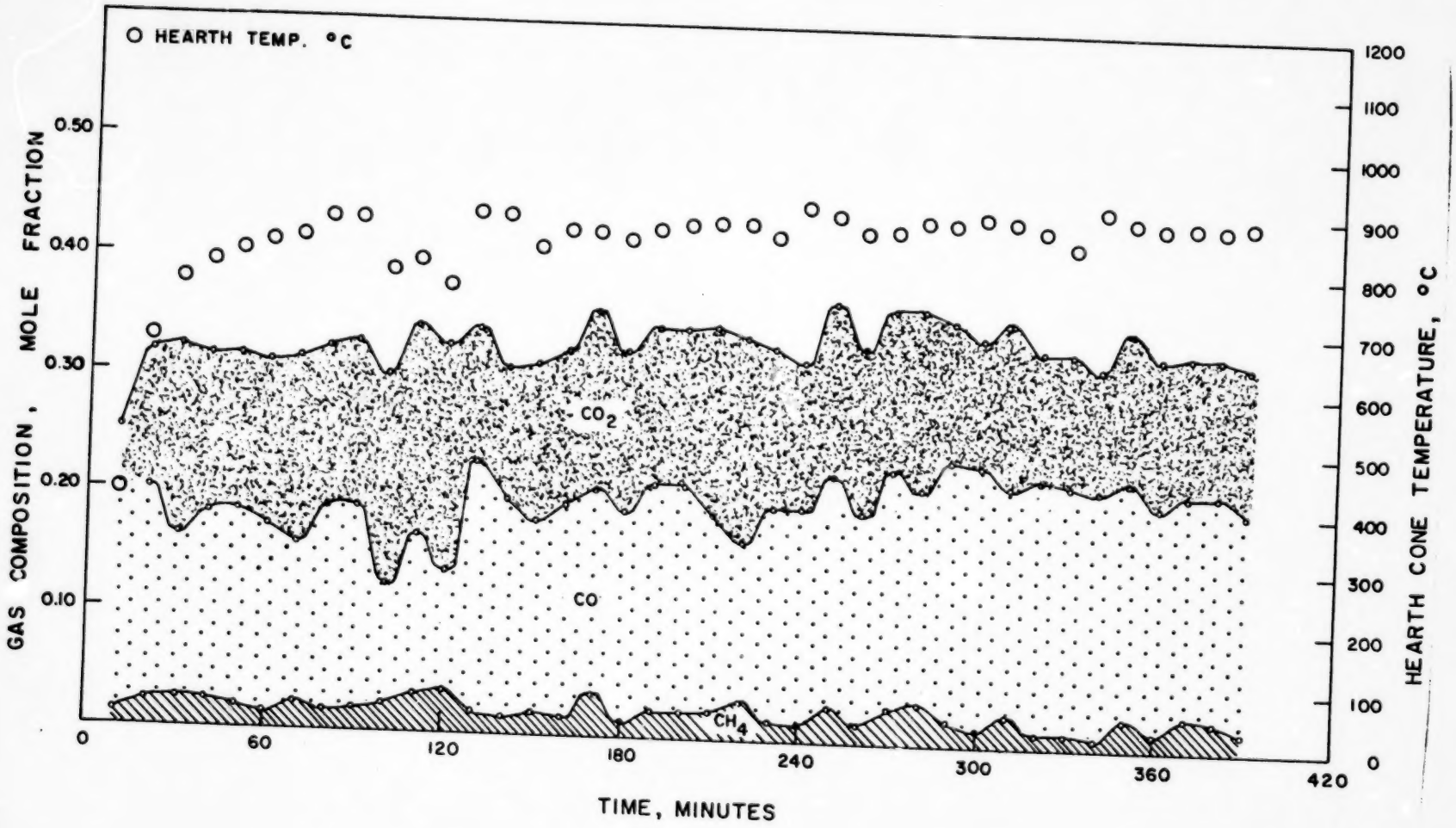

Figure C.13. Gas Composition and Temperature Profile Run 20TA-22